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SYSTEMS PERSPECTIVES ON RENEWABLE POWER

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Edited by Björn Sandén

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PREFACE

Electricity, the lifeblood of industrial society, powers an increasing variety of human activities. In despite of measures to improve energy efficiency, global demand for electrical power will likely continue to grow in decades to come. While electricity in itself is a clean and convenient energy carrier, its production is laden with environmental, social and political problems. This calls for a radical transformation from fossil and nuclear to renewable sources of electrical power.

A transition to renewables, however, is not without problems. Numerous questions demand an answer: if there is enough renewable energy to replace all non-renewables; what environmental impact that may be caused by the production and use of novel types of power plants; how supply and demand of electricity is balanced when large amount of intermittent power is connected to the grid; how the political power of the incumbent industry is balanced by other forces; and what is required from policy makers and investors to build large new systems.

There is not one final answer to questions like these. However, studying renewable power from different systems perspectives can help out in killing myths, clarifying controversies, deepening understanding and formulating new and more precise questions. The sixteen chapters of Systems Perspectives on Renewable Power 2014 address different topics related to the profound question whether electricity, and eventually all energy, can and should be supplied from renewable energy sources, and what is required to realise such a future.

Systems Perspectives on Renewable Power is an evolving ebook with annual updates. You may also want to read Systems Perspectives on Electromobility and Systems Perspectives on Biorefineries.

Björn Sandén
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ASSESSING RENEWABLE POWER

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It is fair to say that nowadays electricity, more than oil, is the lifeblood of industrial society. Electricity drives the machines of industrial enterprises, heats and cools the spaces where we live and work, enables computing and communication over vast distances and powers an almost infinite set of tools and toys. Soon, also a large share of the transport of goods and people could come to rely on electricity.[1]

World electricity consumption has increased by three per cent annually, almost doubling over the last twenty years. Measures to improve energy efficiency might curb growth of demand but with a growing world population, increased economic activity and a shift from other energy carriers to electricity, demand for electrical power will likely continue to grow in decades to come.

While electricity in itself is a convenient energy carrier that can be used without emissions of pollutants and greenhouse gases, its production is laden with environmental, social and political problems. Two thirds of the electricity consumed globally is still produced from fossil fuels and eighty per cent is produced from non-renewable energy sources. This calls for a radical transformation of electricity supply in the coming decades. Climate, pollution, safety, security and cost issues related to fossil fuels and nuclear power constitute strong drivers to harness renewable flows of energy for power production all over the world (Chapter 2).

Electrical power produced from biomass is gaining increasing interest and recently surpassed one per cent of world supply. While being renewable if managed properly, bioenergy is, like fossil fuels, a chemically stored form of energy with unique benefits and drawbacks. Therefore, bio power and the use of biomass in general, is not included in this book but is dealt with in detail in another book in the same ebook serie.[2] The focus of this book is instead the potential and implications of converting naturally occurring energy flows directly into electricity.

1 See Systems Perspectives on Electromobility.
2 See Systems Perspectives on Biorefineries.

Hydro power has been around since the dawn of electricity production in the 19th century and currently supplies a sixth of world electricity demand. While hydro power production continues to grow (Chapter 4), its ultimate technical potential is fairly limited (Chapter 3) and social and environmental concerns may further constrain its expansion (Chapters 3 and 6). Also geothermal power has increased steadily over many decades, although on a smaller scale. In contrast, most of the many forms of ocean power technology are still in an experimental phase, but with an increasing number of demonstrations initiated all over the world (Chapter 4). The most important development, however, is the rapid growth of wind and solar power over the last two decades. Although their shares of world electricity supply at the end of 2013 were only about three per cent and a half per cent, respectively, the exponential growth, rapid price drops and huge potential which vastly exceeds current electricity supply, signal the entry of a possible game changer (Chapters 2-3).

The inclusion of renewable power that varies over the day and year and with shifting weather conditions, so called intermittent power, presents a challenge to the current power system which was developed around fuel combustion and controllable hydro power. The challenges cover a wide spectrum of time constants: from the milliseconds and seconds relevant for power quality and grid stability to energy balances over days and seasons (Chapters 5 and 9). There is a demand for new solutions to transmit and store electricity, but also new ways of aligning demand and supply as well as combining different forms of power production (Chapters 5, 9-12).

A perhaps even greater challenge for the incumbent industry is the possible shift from centralised to decentralised power production. Modular technologies, such as solar photovoltaics (PV), open up for radically different system configurations, with millions of small producers linked in networks or forming numerous independent systems with local storage. This threat is met by industrial actors and the political system in different ways, but as in all profound societal transformations, there is bound to be battles over institutions, i.e. fight over the laws, regulations and norms that frame what is considered viable, affordable, profitable and desirable (Chapters 2, 13-14).

While in most cases profoundly less harmful and risky than fossil fuels and nuclear power, renewable power systems will not be without environmental impacts (Chapter 6). The energy use and associated greenhouse gas emissions in the production of renewable power plants is, in general, small and may decrease even further in the future, but can under certain circumstances be of relevance for specific installations (Chapter 7). More importantly, considerations of the local environment in the selection of sites and design of installations is a critical issue for most renewable power technologies (Chapters 6 and 8).

The renewable power technologies have different characteristics. Solar power has such a large potential, and even global distribution of that potential, that it can replace all non-renewable energy (not only electricity). It can even allow for a sustainable global industrial society where ten billion people use as much energy as people in present industrial societies (Chapter 3). Also wind energy has a large potential and is available in most geographical settings. The other energy forms are locally concentrated, and while they can never contribute with a very high share of electricity supply, they can be of local importance and, in addition, help balancing demand and supply. The Nordic hydro power resource is an example of this (Chapter 11).

Despite the large potential and many benefits, development and diffusion of renewable power will require policy support. Different technologies will require different types of support, and typically one type of policy intervention is not enough. Here we provide one example: what is required for a large scale diffusion of off-shore wind power in Sweden and in the Baltic Sea (Chapter 15)? The case of off-shore wind power is also used to illustrate the need for financial and human resources in the very large scale transformation processes that will be required to develop electricity and energy systems based on renewable power (Chapter 16).

In summary, there are great opportunities to transform the electricity system and eventually the complete energy system. The natural energy flow resources are immense, there are technologies available and their economics is steadily improving. We might be on the verge of a new industrial revolution,[3] but as in all revolutions, there will be mistakes made, hurdles to pass and conflicts to solve. It is our hope that books like this might help out in the process.

3 Sandén, B.A. (2008). Solar solution: the next industrial revolution. Materials Today 11:22-24.

2

DRIVERS AND BARRIERS FOR RENEWABLE POWER

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RENEWABLE POWER MAY PROVIDE FOR GLOBAL LONG TERM PROSPERITY

The use of non-renewable energy will result in resource scarcity, and is often causing immediate environmental deterioration or consequences reducing the economic prospects for coming generations. Renewable energy may provide for wealth for all people in the world and for generations to come. Making this opportunity into reality, by skilful engineering and industrial development of the necessary technologies, is a driving force for many people in the world and the motive for writing this book.

Electricity from renewable sources of energy is the topic here. Renewable in this context implies that it is possible to utilise a source without reducing the future potential of that resource. Some renewable resources are at the same time exhaustible. Unsustainable harvesting of forest biomass may result in permanent deforestation or even desertification destroying the resource, while proper sustainable forest management may result in a continued or even increased renewable resource for future generations.

This book is mainly about non-exhaustible energy resources, such as solar energy, wind energy, hydro power, waves or tidal energy (see Systems Perspectives on Biorefineries for issues related to bioenergy). The future availability of such energy sources are not affected by the utilisation today. Still, in a very long perspective the rotation of the earth and the moon will have the same period and there will be no tides to harvest, and the sun is predicted to change and make the world uninhabitable in a few billion years. But we have no way of influencing these processes, and they are distant in relation to the future opportunities of mankind.

In thermodynamics the first law states that energy is conserved, whatever happens, the total sum of energies afterwards is exactly the same as the total amount before. What is important from a scientific point of view however is that different forms of energy are more or less useful. The second law of thermodynamics says that in all processes the entropy increases, which is the same as that the part of the energy that can be transformed into any other form of energy, the exergy, is lost. This irreversible character of energy transformations is vital to the understanding of energy systems in nature or society.

Our planet enjoys an inflow of energy in the form of solar radiation with little entropy.[1] By many different energy transformations this radiation is converted into heat with increasing entropy until it is finally radiated into space at other wave lengths as energy useless to us. However, the solar radiation drives winds, the hydrological cycles and provides the exergy necessary to form molecules in plants that is the main source of useful energy to the living ecosystems on earth (Chapter 3).

Electricity is a form of energy that can be fully converted into any other form of energy, it has no entropy and is therefore 100% exergy. Producing electricity from other forms of energy is done in different ways with different efficiencies. In a hydro power plant, turbines and generators typically convert more than 90% of the potential energy of the water into electricity. In a thermal power station where fuels are used to boil water 25-50% of the energy released in the boiler may end up as electricity, while a solar PV panel may typically transform 10-20% of the solar energy hitting the panel into electric energy (Chapter 3-4).

If we have a fixed amount of oil, high energy efficiency is important, as it decides the total benefit we can get from the oil consumed. However, putting a PV-panel on a roof where 100% of the solar radiation was otherwise directly converted into useless heat, the energy efficiency is less important. Instead, cost efficiencies in terms of other costs to achieve the electricity generated are of interest.

That electricity is produced from a renewed source of energy is not sufficient for the societal energy supply to be sustainable. There may be relevant material constraints on the conversion technologies that may result in unsustainable use of renewable energy sources.

Elements, such as various metals are only produced or consumed in nuclear reactors. That renewable energy technologies rely on use of metals is not a sustainability problem as long as the metals are managed in such ways that they are recyclable. The limitation to what is possible to recycle is partially a matter of the exergy necessary to re-concentrate the metal. Ample availability of electricity with, at least temporary, low marginal cost could make more re-cycling economically achievable.

However, processes to produce the equipment must be managed so as to avoid unsustainable pollution practices in order to prove sustainable (see Chapter 6 on environmental issues in general and Chapter 7 on life-cycle energy and greenhouse gas balances in particular).

1 Karlsson, S. (1990) Energy, Entropy and Exergy in the Atmosphere. Thesis, Chalmers University of Technology. See also Chapter 3.

MARKETS FOR ELECTRICITY

During most of the twentieth century, electricity systems were operated as large, vertically integrated monopolies. They were vertically integrated as the same company controlled the electricity grid and sold electricity to the consumers. Most often, they also controlled the electricity production facilities in order to be able to command production that matched demand in order to keep voltage and frequency stable.

The grid was monopolised, as it was difficult and uneconomical to run parallel power grids. The power generation was monopolised to manage balance by commanding production facilities, but also as the thermal power plants that dominated the global electricity generation during the last century presented significant economies of scales, making competition difficult to achieve. Economies of scale refers to the situation where the competitiveness of a production facility increases the larges the facility is.

During the last decades this has changed. Significant cost reductions among technologies to utilise wind and solar energy have provided competitive alternatives without the economy of scale of thermal plants thus making competitive electricity markets feasible. Information technologies for metering and data management have made possible the control of how suppliers and customers live up to the required balance of supply and consumption to keep the power grid stable. Finally, the re-regulation of electricity markets, with the purpose of separating the grid as a regulated monopoly while establishing a competitive electricity market for producers and consumers of electric power, has enabled this development (see also Chapter 13).

In the most open of such markets any electricity consumer is free to choose who to buy electricity from, at what prices and under what other conditions. There is only one compulsory condition on such contracts and that is that someone has to take on the balancing responsibility. This responsibility is often assumed by the supplier. The supplier will then try to match the consumption of the customer at any moment in time. A Transmission System Operator, TSO, will check that the system is in balance and if some fail to balance in a contract the TSO will charge the failing party to pay for the balancing cost that occurred.

POWER AND ENERGY

Energy transformed or transported per unit time is called power. While energy is bought and stored as fuels, an electricity grid demands balance of production and consumption at each moment in time. If that balance of power is not kept, the voltage or frequency will change which in turn may result in other components failing and ultimately to a black-out. Much of what follows in this book is about the importance of power balance in an electricity grid and ways of achieving that balance (see Chapter 4 and 9-12).

PRODUCTION MEETING DEMAND

Last century, the production of most power plants was considered controllable. Consumption on the other hand was not something the monopoly power companies could control. As demand varied with time and weather the power company would adjust production to meet demand. Power plants were deployed in a merit order with the plants of lowest marginal cost of production first, typically coal fired power stations or nuclear reactors with low fuel costs, while power plants with higher fuels costs, those using oil or gas, would operate only when demand was at levels that could not be satisfied with cheaper sources (Chapter 11). Hydro power plants can serve different roles depending on availability of water in reservoirs and expected value of that water at later moments in time.

During the previous century one would spend a lot of money on investments in plants that had low fuel costs and expect them to operate almost every hour of the year to meet the base load in the system. The greatest threat to the stability of electricity grids was considered the sudden failure of the largest power plans or transmission link in the system. Often the largest nuclear reactors and largest coal fired station would dictate how much of reserve capacity was required to be on line to ensure the grid would not collapse if there was a sudden failure. The 1400 MW nuclear reactor currently under construction in Finland even requires a new power line to be built from Sweden as the Finnish grid otherwise would not be able to handle a sudden stop of the reactor.

BASE LOAD POWER PLANTS IS AN OBSOLETE TERM

As new power plants with zero, or close to zero, marginal cost of production have come into the electricity system, even the old kinds of "base load supply" are out-competed. When available, solar and wind will produce at lower cost. They will save costs as their production makes it possible to avoid using production facilities consuming fuels.

For the TSO, the failure of a nuclear reactors or coal fired power station is a major problem as such a failure is unpredictable, sudden, and a relatively large loss of supply. The technical failure of a wind power plant or a solar plant is a minor problem as the loss of supply is relatively small.

However, the solar and wind facilities are not controllable, they are 'intermittent'. When the wind blows they produce, when not – they do not. Even if they are not controllable, they are to some degree predictable.[2] They pose a challenge similar to the consumption. Thus, the challenge of balancing the electricity system may be seen as increasing. As we will show in the following chapters there are many competing opportunities evolving to meet this challenge.

PRICE GUIDING BOTH SUPPLY AND DEMAND

If we had still been in the old kind of non-market setting where demand was out of control and the power company had to manage all the balancing efforts this would result in higher costs of high marginal cost power generation. Most traditional

2 The degree to which renewable power are variable, predictable and possible to control differ between the different forms of renewable energy (see Chapter 3-5). Variability and predictability also depends on the spatial size of the system. Over a large area local variations will even out.

power companies have entered the competitive electricity market with a business model still offering customers to consume power at any time at a fixed price. Some of them are now realising that their contractual position with balancing responsibility for such contracts is threatening their economic survival.

As we will see in the remaining parts of this book there are many technical opportunities to achieve power balance where new kinds of price driven consumption patterns are essential (Chapter 10). While the electricity spot market pricing has until now mainly been seen as a public mechanism to achieve a rational order of deploying power plants, we will see more interaction of consumption relating to the cost of power in the years ahead of us.

COSTS OF NON-RENEWABLE ENERGY AND POLICY

Governments have had attention on energy policies for many centuries. Energy, or rather exergy, is an essential resource for society. What is now conventional energy supply, from limited deposits, once opened for economic development that earlier available energy technologies could not provide. Since some decades, the challenges to continue relying of these sources have accumulated.

ENERGY SECURITY OF SUPPLY

Of the fossil fuels, oil is concentrated in a few regions of the world. In most oil rich regions, the resource has become the economic basis for less democratic regimes and sometimes established by military interventions. The indirect costs to support continuous flow of oil to the import dependent countries have proved significant while still not ensuring security of supply.

Renewable energy is available everywhere. While some parts of the world have more sun, others have more wind resources and yet other parts of the world are rich in biomass. Specific locations may also be endowed by hydro and osmotic power, geothermal energy and various forms of ocean energy (Chapter 3).

ENERGY SCARCITY PRICES BLOCKING GROWTH

The limited resources of non-renewable fuels provide negative feedback on economic success, as prices tend to increase with increased consumption. For the government in China, aiming at providing a dramatically increased standard of living for another half a billion inhabitants, the prospects of that negative feedback calls for alternatives.

As we will describe in the following pages, energy supply cost of renewable electricity are not increasing with increased utilisation as large resources remaining to be utilised, and technology costs are decreasing with experience. There are limits beyond which this will not hold, but in particular for solar energy they are well beyond the possible utilisation in the coming decades.

ENVIRONMENTAL COSTS OF FUELS MAY OUTWEIGH ECONOMIC GROWTH

Another driving argument is the negative environmental feedback may take many forms. Local air pollution, climate change from greenhouse gas accumulation in the atmosphere or the costs and health effects of nuclear reactor core accidents have made the development of renewable energy technologies a major global activity (see also Chapter 14 on environmental costs).

Though security of supply, resource scarcity and environmental feedback may get different attention in different parts of the world, they contribute to the consistent support for the development of renewable energy technologies.

LEARNING ENERGY TECHNOLOGIES BY EXPERIENCE

As in many industries over the centuries, renewable energy technologies have become lower cost options the more experience that have accumulated. In the book "Industrial learning curves for energy technology policy" published by OECD in 2000, Claes-Otto Wene provided evidence that the wind and solar industries would become competitive with conventional energy technologies.[3] When this would happen could not be predicted, as learning does not come with time but with experience. Experience requires investments before competitiveness is reached, something that may be achieved on niche markets. Niche markets may emerge due to specific performance characteristics (e.g. solar cells in space), develop out of demand from idealists and other early adopters, or be created through subsidy schemes set up by governments (see also Chapter 14-15 on learning and industrial development).

THE GLOBAL DEVELOPMENT RELAY

Regarding wind power, the modern industry started in Denmark in the 1980s. Initiated by idealists aiming to prove that wind power was technically feasible the industry later received government support and evolved into a commercial sector still making Denmark the home of a couple of the leading global suppliers of wind power plants. In the following decades, other countries took the lead. Irregular investments in the US were followed by more constant efforts in Germany and Spain and, in the last decade, in China.

Just as one could see from the early diagrams of learning the result is that wind power is now the cheapest source of new electric power in many parts of the world, with total cost of electricity reported as low as 3-4 eurocent (4-6 US cents) per kWh.[4]

A similar relay of industrial policy driven developments can be noted in the solar PV sector. Here, the first efforts were aimed at providing electricity for space crafts commissioned by the US. During the 1970s research and demonstration efforts resulted in early outdoor deployable panels that found niche-markets during the 1980s and 1990s. By the end of the 20th century the first government initiated roof-top programmes in Japan and Germany started to make the market grow.

3 Wene, C.-O. (2000). Experience Curves for Energy Technology Policy, International Energy Agency. See also Sandén, B. A. and Azar, C. (2005). Near-term technology policies for long-term climate targets - economy wide versus technology specific approaches, Energy Policy, 33:1557–1576.

4 US DOE (2013). 2012 Wind Technologies Market Report.

Despite the high anticipated costs, Germany launched a system with guaranteed feed-in tariffs (FITs) paid to anyone who supplied electricity to the grid from solar PVs in 2000. The estimated costs were high, and the generous feed-in tariffs resulted in large scale investments and quickly dropping prices spurring further investments. Despite dramatic cuts in FITs over the year German households will continue to pay for installations done during this initial phase on PV industrialisation for many years to come (see Chapter 13-14 for further discussions on the politics of renewable energy in Germany).

The result, however, of the policy driven German development is that solar PV cost have come down for all potential customers around the world. This has opened opportunities for hundreds of millions of people without access to an electricity grid to get light, radio, TV and mobile phones powered by affordable PV electricity.

It has also resulted in the cost of solar PV electricity in a few countries with high insulation reaching "wholesale grid parity" or "busbar parity", implying PV investments being competitive with other sources of new power generation without subsidies, also in Europe. In even more countries "consumer grid parity" or "socket-parity" is reached, meaning it is cheaper to produce electricity than to buy from the grid.[5] Many expect this to be the early steps of an un-subsidised solar revolution that is no longer controlled by government policies and may have significant impact on all electricity markets and power companies in the world.

Thus the policies in just a few countries supporting renewable electricity have made the continued large scale deployment economically feasible without further subsidies or policy support. This is irreversibly altering the global energy market conditions.

RENEWABLE POWER AS DISRUPTIVE INNOVATION

In the book The innovators dilemma – how new technologies cause great firms to fail, Clayton Christensen describes the characteristics of disruptive innovations that broke down established industries.[6] He says the evolving technologies were systematically discredited, typically because they were too expensive, not up to conventional standards and, not least important, they did not fit the business models of the established companies. Solar and wind power fit this description well. Too expensive, intermittent, and decentralised thereby out of scope for the incumbents.

Still, the evolution and reduced cost, new investing actors and a re-regulated market have made the change possible. This is now threatening power companies. The book Explosive Growth by Michael and Susan Rogol published in December 2011 gave power companies 1000 days to modify their business models or perish.

POLITICAL POWER OF POWER COMPANIES

While some expect the continued development to run fast, there are reasons to expect further obstacles to the development. Many of these may come from the

5 Deutche Bank (2014). Let the Second Gold Rush Begin.
6 Clayton Christensen (1997). The Innovators Dilemma - why great firms fail.

old power companies using their traditional powerful position in relation to national governments to slow or stop the processes that may deprive them of market shares, results and ultimately the value of their balance sheets (Chapter 13-14).

Governments may easily be convinced to remove support and introduce barriers towards new renewable supplies. Not only are some governments still owners of the incumbent power companies, these companies may, if going bankrupt, leave significant toxic assets in the hands of ill prepared governments – this may be coal mines or nuclear wastes where economic liabilities are uncovered or underestimated.

Mechanisms to block development of new renewable electricity may be demands from the incumbents to remove support mechanisms and subsidies, introduce new taxes or even retroactively change tariffs, examples are provided in Spain and a number of other European countries; allowing the power companies or related grid companies to veto new connections to the grid as is done in Japan; introducing subsidies for keeping old fossil fuelled stations on line to avoid that over-committed suppliers have to face costs of failed balancing that they are not able to handle, as European companies propose under the heading "capacity market" (see also Chapter 9 and 13-14).

INSTITUTIONAL INERTIA

While the electricity market reforms in the world have provided the opening of power markets for new actors there are still institutions and regulations that are not supporting or allowing the new technological opportunities. Such rules may block applications of new energy technologies, but may also result in individually rational and profitable, but from a systems perspective less efficient, solutions.

Examples may be electricity consumption taxation introduced for purposes of simulating carbon pricing on electricity generation, now being applied to households supplying solar electricity via the grid, or VAT-regulations that punish exchange of day-time peak power from family houses for low cost night time power.

Such rules will delay deployment. But such incentives may also result in households being tempted to invest further into batteries and disconnecting from the grid, though it would be economically more efficient to use the grid to balance supply and demand (see also Chapter 4 and 9).

Other examples of legislation of relevance may be regulation on land use that prohibits the application of solar energy installation to what could be agricultural land. Another is how the real estate and building and planning laws regulate the right of solar irradiation for estate owners who have invested in solar energy. There are also regulations related to electrical installations that may provide significant economic barriers for solar installations.

The ability of legislating bodies in the world to efficiently identify and adapt legislation, so as to remove barriers, is now more important than legislation on subsidies and support. Removing barriers reduces societal costs, while support and subsidies is redistributing costs that have not been avoided.

PROSPECTS OF EVOLUTION

The opportunities to avoid the severe constraints on global economic development posed by conventional energy sources by utilising renewable power instead, will provide strong driving forces for continued development.

This transformation will pose a magnificent challenge for incumbent industries in the sector, and attempts to block or slowdown development will occur. Even without such deliberate attempts to block development there are real needs to develop auxiliary technologies and institutions to facilitate efficient deployment of new renewable energy in the electricity sector.

This e-book is about these challenges and opportunities. They are described and analysed, hopefully contributing to the reduction of barriers by providing knowledge of possible solutions.

3

ARE RENEWABLE ENERGY RESOURCES LARGE ENOUGH TO REPLACE NON-RENEWABLE ENERGY?

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INTRODUCTION

While the very large potential of renewable energy has been known to some scholars at least since the end of the 19^{th} century, the potential is still today commonly underrated in public debate. To get the physical proportions right is a necessary first step in a sensible discussion on possible and desirable development paths.

The primary purpose of this chapter is to answer the question if the resources of renewable energy flows are large enough to completely replace fossil fuels and nuclear energy, and to indefinitely support a world population of 9-10 billion people at a living standard equivalent to present day industrialised societies. A second purpose is to outline what expectations we may have on each of the different renewable flow resources.

The potential of the conversion route via bioenergy is excluded from this discussion but is thoroughly treated in Systems Perspectives on Biorefineries.[1] Our scope is limited to potentials of electricity production, but since electricity is an energy form of high quality (see Chapter 2) its use is versatile. It is not unlikely

1 Systems Perspectives on Biorefineries, Chapter 4.

that many applications that today are powered by the chemical energy in fuels will switch to electricity in the coming decades (see for example Systems Perspectives on Electromobility). Electricity can also, at a cost, be converted to chemical energy stored in hydrogen or even hydrocarbons (see Chapter 12). Hence, a comparison makes sense not only to the global electricity demand, but also to the total energy demand.

RESOURCE ASSESSMENT

The renewable energy flows have three different origins. Most renewable energy can be traced back to the influx of solar energy at the top of the atmosphere, an energy flow about 10 000 times larger than society's current use of primary energy (Table 3.1). The solar energy inflow is converted to a range of secondary energy flows, including winds, waves and water streams and currents. The geothermal energy flow derived from the hot interior of the Earth and the tidal energy originating from kinetic and gravitational energy in the Earth, moon and sun system are several orders of magnitude smaller.[2]

Table 3.1 Three primary energy inflows are the origins of all renewable energy sources.

Primary renewable energy influx	Annual flow (10^3 TWh/yr)
Solar energy - entering the Earth's atmosphere	1 500 000
Geothermal energy - transported to the surface of the Earth	400
Gravitational energy - converted to tides at the surface of the Earth	32

The objective of this chapter is to estimate somewhat realistic resource potentials; how much of the energy flows in Table 3.1 can be converted to electricity? Here we must admit that "resource potential" is an elusive concept and numerous attempts have been made in the literature to define and assess different types of potentials. An important starting point is to free the imagination from 'the prison of the present' and avoid confusing a realistic future potential with what is currently technically realised or what is believed to be economically competitive in the near term. A commonly used logic is then to start with some kind of ultimate physical potential and then add different kinds of limitations. In this chapter we will follow this route and try to identify what we here term physical potentials, technical potentials and socio-economic potentials. In this way, we will proceed from the hard facts of natural science to more socially constructed constraints, and thereby indicate different levels of flexibility.

The measure we here term *physical potential* tries to capture the part of the physical energy flow that theoretically could be converted to electricity. In some cases this is fairly straightforward, in other cases we need to rely on recently published

2 To be more precise, also the exchange of heat radiation with the cold universe is a source of exergy ('useful energy', Chapter 2) that contributes to the geophysical processes on Earth. To some extent the kinetic or gravitational energy of the Earth also contribute to ocean currents and waves, wind energy and rainfall, and a minor part of the tidal energy from gravitational interaction is dissipated as friction heat in the solid Earth contributing to geothermal energy, see Hermann, W. A. (2006). Quantifying global exergy resources, *Energy* 31(12):1685–1702.

results based of advanced models. In almost all cases we exclude parts of the resource that we find highly unlikely as a basis for electricity production at any significant scale, for example, solar energy captured in the atmosphere, wind energy in high altitude jet streams and wave energy dissipated over the deep oceans.

In the *technical potential* we try to exclude parts of the resource that has not yet been conceived for electricity production. For example, solar and wind power over the deep oceans are excluded. Furthermore, we apply demonstrated conversion efficiencies instead of theoretical maxima. In most cases we rely on thorough assessments conducted by others that comply with these criteria.

It is not reasonable to view the technical potentials as feasible targets. There will be numerous economic, environmental and social concerns that will limit the amount of energy we ever would like exploit. To give a hunch of the order of magnitudes of electricity that we could expect from the different sources we have tried to derive *socio-economic potentials.* These are not based on current technology costs and electricity prices, but on the assumption that the conversion technologies will be able to compete in favourable locations, but will have to share the surfaces and landscapes of the Earth with other social activities and undisturbed nature.

This chapter does not explicitly take energy system integration into account. Obviously, utilisation of renewable flow resources on a very large scale will require storage and transmission technology and maybe changed temporal patterns of demand. We return to spatial and temporal characteristics of the different resources towards the end of the chapter (see also Chapter 5 and 9-12). Furthermore, the assessment lacks a time dimension. Developing the huge technical systems required will at least take several decades (see Chapters 15-16).

The numerical estimates are provided in the Table 3.2. With the exception of hydro power, only a minor fraction of the potentials have been utilised. The potential of solar power is large compared to current electricity and energy use; also the wind power potential is significant.

World energy demand, however, is expected to increase. If 9-10 billion people used as much energy as an average Swede use today, the primary energy supply would almost quadruple.[3] Nevertheless, demand would still not exceed the estimated socio-economic potential of solar power.

While the global potentials of the other power sources are of a different order of magnitude, they may be of local importance. The sections below elaborate on the derivation of the numbers and include a discussion on geographical and temporal variation of the different energy flows.[4]

3 The energy scenarios in IPCC (2000) special report on emission scenarios approximately span a range from 150 000 – 600 000 TWh/yr of primary energy supply in 2100, with the high end thus corresponding to a quadrupling of primary energy supply.

4 The subdivision in sections happens to bear some resemblance to the classical ‘four elements’: fire, air, water and earth.

Table 3.2 Physical, technical and socio-economic potentials of electricity production from renewable energy flow resources compared to the realised production in 2012 as well as to total world supply of electricity and primary energy in the same year. See text for references, calculations and explanations.

	Potential			World Supply
(10^3 TWh/yr)	Physical	Technical	Socio-economic	2012**
RENEWABLE ELECTRICITY				
Solar (at surface)	730 000	20 000	1000	0.09
Wind (near surface)	2 000	700	100	0.5
Water				
Hydro	50	16	8	3.7
Osmotic	30	2	0.4	-
Wave (near coast)	32	2	0.4	-
Tidal	22	1	0.2	0.001
Ocean current	40	*	*	-
Ocean thermal (OTEC)	120	*	*	-
Geothermal	60	2	1	0.06
WORLD ENERGY				
Electricity				23
Primary energy				150

* Could not be assessed (see text).
** Source: PB statistical review of energy (2013).

SOLAR POWER

The solar constant, i.e. the irradiance at the top of the atmosphere, is measured to about 1360 kW/m^2.[5] Multiplying with the cross section of the Earth this amounts to a total inflow of about 1500 million TWh/yr (Table 3.1). For space-based solar power this constitutes the ultimate resource limit. However, solar satellites that harness the solar energy outside of the atmosphere and beam it down to Earth are still only at the drawing table.

Averaged out over the surface of the Earth, the irradiation at the top of the atmosphere corresponds to 340 W/m^2. Earth bound solar power plants need to let go with the 55%, or about 190 W/m^2, that reaches the Earth surface, summing up to 840 million TWh/yr.[6] The rest is absorbed in the atmosphere or reflected out in space before it reaches the ground. The irradiation at ground level has two components, direct and diffuse light. While conventional flat plate solar cells can harness the energy in both components, technologies that concentrate the light beams such as concentrated solar thermal power or concentrated photovoltaics can only make use of direct radiation (Chapter 4).

5 In a sense, this is 'the mother of all energy constants'. Nevertheless, new knowledge has revised also this number. Recent measurements indicate a value of about 1362 W/m^2 and a slight downward correction of the earlier estimate of 1366 W/m^2. Kopp, G. and J.L. Lean (2011). A new, lower value of total solar irradiance: Evidence and climate significance. *Geophysical Research Letters*. 38(1): L01706.

6 Stephens, G.L., et al. (2012). An update on Earth's energy balance in light of the latest global observations. Nature Geoscience 5:691-696, report 188±6 W/m^2. Our estimate is 189 W/m^2 based on insolation data from NASA (2013). NASA Surface meteorology and Solar Energy: Global Data Sets.

The theoretical limit for conversion of direct and diffuse light to electricity at the surface of the Earth has been estimated at 93% and 75%, respectively.[7] About two thirds of the energy at ground level is direct radiation. Hence we can identify a physical potential of 700 million TWh/yr (Table 3.2).

The solar cell modules and solar thermal power plants that are commercially available today typically have conversion efficiencies between 10 and 20%, while the highest recorded efficiency of a small cell in 2013 was 44%.[8] In, principle solar cell modules can be put side by side, e.g. on roof-tops, but on large solar farms, some additional spacing is normally required. Current large solar electricity plants in the US have a module area to land area ratio of 20-50%.[9] Where land is scarce, a packing density in the upper end of the range is more likely. In conclusion, with current technology an overall conversion efficiency of 10% is feasible over large areas, implying an average production potential of about 20 W/m^2.[10]

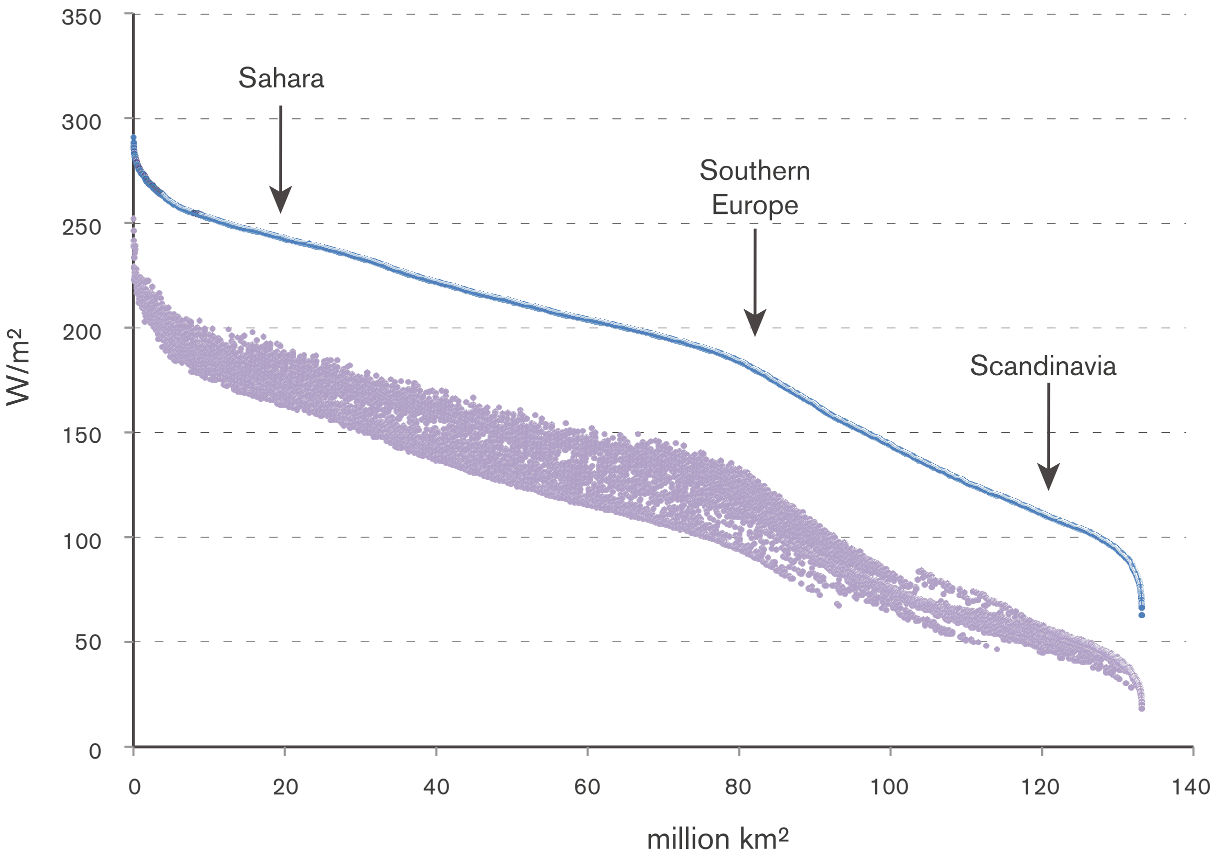

Figure 3.1 The distribution of total solar energy irradiance (blue line) and the part made up of direct light (purple dots) (in W/m^2). The total land area of the Earth north of Antarctica is included and divided into 17346 grid points, 1x1 degrees in size. Source: Based on data from NASA (2013).

The physical potential implies a complete coverage of the globe. In principle, there is nothing hindering solar power at sea. There are prototypes and plans

7 Hermann, W. A. (2006). Quantifying global exergy resources, *Energy* 31(12):1685–1702.

8 Green, M.A. et al. (2013). Solar cell efficiency tables (version 42). Progress in Photovoltaics: Research and Applications 21:827-837.

9 Ong, S. et al. (2013). Land-Use Requirements for Solar Power Plants in the United States, NREL.

10 The 10% could e.g. correspond to a system with 10% efficiency and 100% packing density or one with 20% efficiency and 50% packing density.

for off-shore solar power and floating solar cells may prove to be less technically demanding than e.g. wave and off-shore wind power. However, besides small installations on boats and oilrigs and some systems attached to the shore, to date all solar power plants are located on land. Land (excluding Antarctica) covers 26% of the Earth and actually receives the same fraction of the energy inflow.[11] A conversion of 10% then results in an onshore technical potential of 20 million TWh/yr (Table 3.2).

The distribution of the solar energy resource is depicted in Figure 3.1. About 98% of the total irradiation is supplied at an annual intensity above 100 W/m². Since solar energy is currently harnessed even in Scandinavia in the far right of the graph (about 115 W/m²), there are basically no land areas that can be excluded from the resource base. However, the figure also shows that the direct irradiance is typically 50-90 W/m² lower than the total energy inflow, implying that the share of direct radiation decreases with decreased irradiance. Hence, technologies that concentrate sunlight are likely to be relatively more competitive in sunny areas.

Given that solar electricity can be produced almost anywhere, including the surfaces of buildings, infrastructure and vehicles, as well as on land of low value, it is difficult to justify any particular limit to production below the technical potential. However, some comparisons could indicate a reasonable socio-economic potential. In 2012, 5% of the area of EU was covered by 'artificial land' (buildings, roads etc.);[12] a third of the global land area is covered by deserts; and it has been suggested that an area corresponding to 6% of all land north of Antarctica could be available for bioenergy production.[13] Covering 5% of the global land area of any type, including sunnier and less sunny areas, with solar power plants with an overall conversion efficiency of 10% would constitute a socio-economic potential of more than 1 million TWh/yr (Table 3.2).

WIND POWER

Wind energy is driven by pressure difference caused by uneven heating and cooling of the Earth atmosphere. Thus, it originates from solar energy, and around 1% of the solar energy inflow, or some 14 million TWh/yr, is estimated to be converted to wind energy.[14] This energy is ultimately dissipated through friction (or drag) in the moving air itself and between the moving air and land and water surfaces (see wave energy below). Extraction of wind power would effectively mean an increased drag. There are two ways to calculate the ultimate potential to convert wind energy to electricity: top-down and bottom-up approaches.

11 Based on data from NASA (2013).

12 See news release from Eurostat (2013). In Sweden, suitable roof-tops could provide some 40 TWh/yr (Kjellson, E., 2000, Potentialstudie för byggnadsintegrerade solceller i Sverige, Lund University). Areas covered by railways and larger roads could supply another 100 TWh/yr. In energy terms, this would cover the Swedish electricity consumption. However, power supply will not match demand and therefore storage would be required to utilise this resource (see Chapter 5 and 9-12) One can also note that if all land had the same area coverage of solar cells as Germany had at the end of 2013, solar cells would produce about 20 000 TWh/year, almost corresponding to global electricity production in 2012 (Table 3.2).

13 In the IPCC (2011) special report on renewable energy (p. 226), an area of 7.8 million km² (or 6% of all land north of Antarctica) is considered to be available for bioenergy production. On this area, 170 EJ/yr of bioenergy could be produced, which in turn could be converted to some 15 000 TWh/yr of electricity. With an area efficiency of 10%, direct conversion of solar energy would produce some 1.3 million TWh/yr on the same area.

14 Marvel et al. (2013). Geophysical limits to global wind power. *Nature Climate Change* 3:118–121.

Top-down approaches start with the observation that at some level of increased drag from wind power extraction, the climate system will not be able to replenish the kinetic energy. A recent top-down study estimated the physical wind power at the bottom 200 m of the atmosphere at 2 million TWh/yr (Table 3.2).[15] Currently there is no technology that can convert wind energy over the deep ocean to electricity.[16] The onshore (90%) and offshore near coast (10%) technical potential was estimated at 700 000 TWh/yr. Adding more turbines at this saturation level would only reduce the production of others.

There could also be other practical issues that would limit the technical potential. Bottom-up approaches starts with maps of average wind speeds in different regions. Every windmill based on the principle of a rotating turbine has a theoretical limit of 59% called the Betz factor (see Chapter 4). In reality, turbines may reach 40-50% under optimal conditions. To harness as much of the wind resource as possible, turbines can be packed in wind farms; however, when densely packed they also steal wind from each other and worsen the economics of each turbine. Hence, there is a trade-off between energy conversion per turbine and energy conversion per land area.

One study estimates the peak power production at 7 W per m^2 of farm area, based on an assumed optimal density of one 2.5 MW turbine per 0.28 km^2 and a farm loss of 20%. In most places, the average production would be much lower, since 7 W/m^2 of farm area corresponds to a wind speed of more than 10 m/s. The energy in the wind is proportional to the cube of the wind speed (see Figure 3.2 and Chapter 4, Box 4.1). Hence, the energy in the wind falls quickly with lower wind speeds. At 6 m/s, the power output the same farm would only reach 1.5 W/m^2 or about 20% of the rated capacity.[17]

An additional result of the relationship between wind speed and energy content is that, compared to solar energy (Figure 3.1), the wind energy resource is less evenly distributed. In areas with low average wind speed, the energy density is very low and economic extraction of wind power is not likely to be feasible. The bottom-up studies thus typically exclude areas in the world with low wind speeds.[18] However, when calculating the theoretical output of wind farm placed in reasonably good locations all over the world, one bottom-up study estimated a technical potential of 800 000 TWh/yr.[19]

15 Archer and Jacobson (2012). Saturation wind power potential and its implications for wind energy, *PNAS* 109(39):15679–15684. The physical potential to capture energy from high altitude jet streams was estimated at 3 million TWh/yr. Currently there are no available technology that can capture energy from high altitude jet streams (if lower energy use in airplanes is excluded).
16 There are several experiments with floating wind mills, still, there is a limit on the depth where these can be placed as well, as they are anchored to the sea floor and secondly there may be economical limitation on how far away they can be placed from the demand.
17 A study of land use of wind energy farms in the US found an average capacity density of 3 W/m^2. With a capacity factor of 30% the average production would be 1 W/m^2, 10 kWh per m^2 and year. Denholm et al. (2009). Land-Use Requirements of Modern Wind Power Plants in the United States, NREL.
18 Since winds speeds generally increase with height, more energy can be extracted with larger (and higher) turbines.
19 The study included onshore (80%) and offshore near cost (20%) areas with capacity factors above 20% but excluded onshore ice, forest and water covered areas. Lu, X., et al. (2009). Global Potential for Wind-Generated Electricity. PNAS 106:10933-10938. A similar estimate is provided by Archer and Jacobsson (2013). Geographical and seasonal variability of the global "practical" wind resources, *Applied Geography* 45:119-130.

According to the top-down studies cited above this should be an overestimation since it assumes extraction above the saturation limit when winds cannot be replenished at the global level. According to the top-down models, the huge wind farms imagined in the bottom-up study would interact and steal wind from each other. We therefore assume a technical potential of 700 000 TWh/yr (Table 3.2).

In practice there are mainly two aspects that limit the socio-economic potential of wind power. In populated areas there are conflicts about siting, while less populated windy areas are remote and require large infrastructure investments. The technical potential derived from the bottom-up study, in fact, requires that about 30% of the land area outside of the polar regions is used for wind power production. Even if wind turbines can co-exist with agriculture, forestry and solar electricity harvesting, such a high penetration is probably not desirable (see also discussion in Chapter 6). From this perspective a socio-economic potential in the order of 100 000 TWh/yr seems reasonable claiming a few percent of onshore and near-cost areas (Table 3.2).

WATER POWER – RIVERS AND OCEANS

Water is a liquid of relatively high density and is a good carrier of kinetic energy (Figure 3.2). Electric power can be produced from natural flows of moving water in several ways, including hydro, wave, tidal and ocean current power. Moreover, heat differences in the oceans can be converted to electric power in ocean thermal energy conversion (OTEC) plants and differences in salt concentrations between rivers and oceans can be used to produce electricity in osmotic power plants (see more on technologies in Chapter 4).

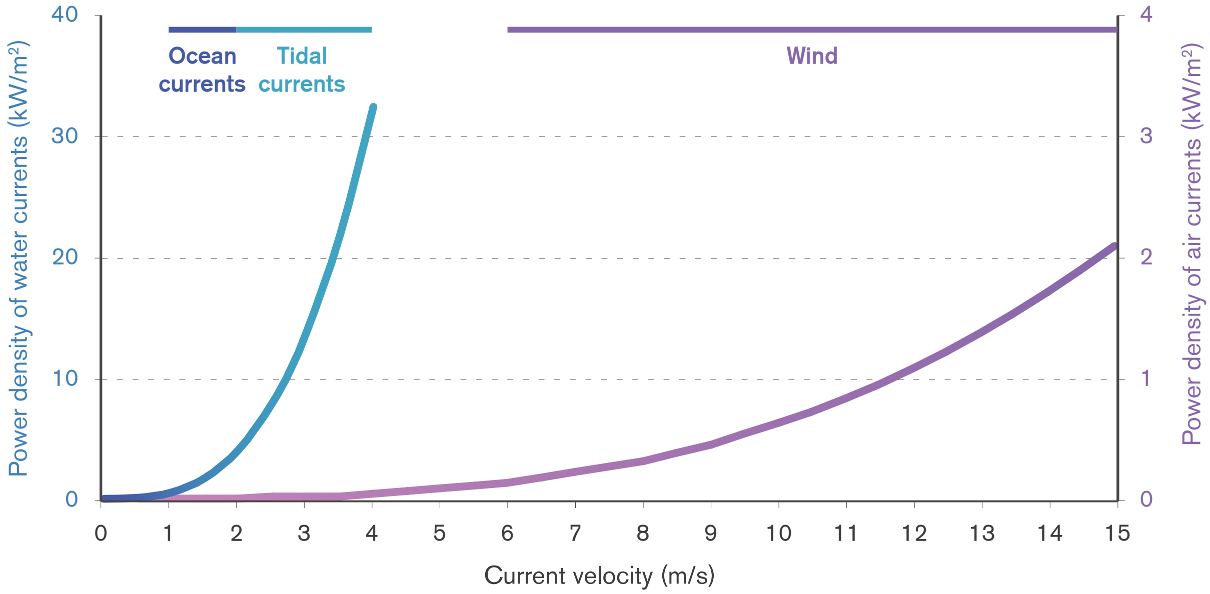

Figure 3.2 Power densities of currents of water and air as a function of current velocity. The power density is proportional to the density of the fluid and the cube of the current velocity (see also Box 4.1). The density of water is almost a thousand times larger than the density of air. Observe that the area in the figure is not the land area discussed in the text but the cross section area of the current.

Hydro power is currently by far the most common source of renewable power and relies ultimately on the solar energy that evaporates water from land and oceans. While almost a fourth of the solar energy influx to Earth is used in the water cycle, only a small fraction can be utilised as hydropower. A large share of the precipitation falls on the oceans, and of the annual precipitation on land of about 120 000 km^3 most is absorbed by soil or vegetation. About 40% remains as runoff water. When accounting for geographical variations in precipitation and altitude, the runoff water provides a physical potential corresponding to some 40 000-60 000 TWh/yr (to pick one number we use 50 000 TWh/yr in Table 3.2).[20]

The conversion efficiency of hydro power plants can exceed 90%, but several site specific factors limit exploitation. Hence, the technical potential has been estimated at 16 000 TWh/yr (Table 3.2). Hydro power is a mature technology and no technological breakthroughs with significant changes of the technical potential can be expected. Nonetheless, advances are being made within small-scale hydropower schemes, indicating that the access to the power source can spread. The global socio-economic potential of hydro power has been estimated at 8000 TWh/yr (Table 3.2).[21] However, this potential is dependent on a multitude of factors that vary in time and are difficult to predict. For instance, costs are influenced by the consideration of environmental impacts, the value of alternative land-use and other sectors' demand for the freshwater resource (Chapter 6). Rivers suitable for hydro power often cross national borders, thus being a source of political conflict. In 2012, 3600 TWh/yr or almost half of the socio-economic potential was utilised (Table 3.2).

Rivers also carry another potential power source. When rivers return freshwater to the salt oceans, the difference in salinity, i.e. the osmotic pressure gradient, can be utilised to generate power. Based on the total runoff water and the power that theoretically can be extracted a physical potential of 30 000 TWh/yr has been estimated. The technical potential has been estimated at 1600-1700 TWh/yr.[22] Continued development of membrane technology will improve the economics. Since osmotic power plants, in contrast to hydropower, need to be situated close to the mouth of the river, where many societal activities are located, we halve the ratio between technical and socio-economic potential used for hydropower to calculate a socio-economic potential of 400 TWh/yr (Table 3.2).

The total transfer of energy from winds to ocean waves is estimated at 500 000 TWh/yr (0.17 W/m^2 of ocean).[23] The physical potential in waves reaching the coastlines has been estimated at 32 000 TWh/yr, with a reduction to 26 000 TWh/yr when areas with very low wave power intensity or ice cover are excluded.[24]

20 Rogner, H.-H. et al. (2012). Energy Resources and Potentials, Chapter 7 in Global Energy Assessment, IIASA; Hermann, W. A. (2006).

21 Rogner, H.-H. et al. (2012).

22 Rogner, H.-H. et al. (2012); Skilhagen, S.E. et al. (2008). Osmotic power – power production based on the osmotic pressure difference between waters with varying salt gradients. *Desalination* (220):476-482.

23 Hermann, W. A. (2006).

24 Mörk et al (2010). Assessing the Global Wave Energy Potential, 29th International Conference on Ocean, Offshore and Arctic Engineering, 3: 447-454. Gunn, K. and Stock-Williams, C. (2012). Quantifying the global wave power resource. *Renewable Energy* 44:296-304, reach a slightly lower physical potential of 18 000 TWh/yr.

Currently, there are no large arrays of wave power converters installed in the world. The few estimates of how much of the total wave energy that reach a cost-line that might be converted to electricity in arrays of devices indicate an overall conversion efficiency of 5-6%.[25] This gives a technical potential of about 2 000 TWh/yr. Since the conversion efficiency of individual devices is much higher, higher packing densities may raise this number. Nevertheless, the socio-economic potential is likely much smaller. The economics of extracting power from waves with low power intensity is unfavourable and in areas with higher intensities, devices need to be sensitive enough to efficiently utilise normal waves and at the same time be robust enough to withstand extreme waves. In addition, competition for the use of coastlines adds another limitation. Applying a similar argument as for solar and wind and taking into account that the wave power resource is geographically more concentrated, a socio-economic potential of 20% of the technical potential, or 400 TWh/yr, might be feasible (Table 3.2).

As Earth rotates through the gravitational fields of the sun and the moon, the surface is set in motion. A total of 32 000 TWh/yr of gravitational origin is dissipated in the Earth-moon-sun system (Table 3.1). Out of this, 22 000 TWh/yr generate tidal waves over the continental shelves constituting the ultimate physical potential of tidal power.[26] Tidal power systems utilise either the potential energy of the tidal wave or the kinetic energy of fast-flowing tides, mainly realisable in bays and straits, respectively (Chapter 4). The technical potential in the UK and Western Europe has been estimated at about 5% of the mechanical energy lost over the shelves which may be extrapolated to a global technical potential of 1000 TWh/yr.[27] Only a fraction of the resource is likely to be economically and environmentally viable. Applying the same reduction as for wave power would yield a socio-economic potential of 200 TWh/yr (Table 3.2).

Ocean currents are driven by solar heating, wind, gravity and the rotation of Earth. The mass transport of ocean currents is immense and predictable but the energy density is low compared to tidal currents due to lower velocities (Figure 3.2).[28] The total energy of ocean currents has been estimated at about 40 000 TWh/yr although this is yet to be verified (Table 3.2).[29] There are no estimates of the technical potential of arrays of ocean current power converters. The slow speed of the ocean currents and the depths of the oceans present an economic challenge. Both costs and environmental feasibility of this power source remain very uncertain and its socio-economic potential cannot be assessed (see Chapter 4 and 8).

25 Beels, C. et al. (2011). A methodology for production and cost assessment of a farm of wave energy converters. *Renewable Energy* 36:3402-3416; Gunn, K. and Stock-Williams, C. (2012).

26 The remaining fraction dissipates in the deep oceans and as friction in the solid Earth (providing a small contribution to geothermal energy) Hermann, W. A. (2006).. Energy in tidal waves over shallow water has been estimated at around 9 000 TWh/yr, Charlier, R. H. & Justus, J. R. (1993), Ocean energies, Elsevier, Amsterdam.

27 Hammons, T.J. (1993). Tidal power. Proceedings of the IEEE 81:419-433; Blunden, L.S. and Bahaj, A.S., (2007). Tidal energy resource assessment for tidal stream generators. Proceedings of the Institution of Mechanical Engineers, Part A: *Journal of Power and Energy* 221:137-146.

28 The Florida Current (part of the Gulf Stream) has been reported to encompass a physical potential of about 120 TWh/yr, Hanson et al (2010). Power from the Florida Current: A New Perspective on an Old Vision, Bulletin of American Meteorological Societty 91:861–866. Other fast-flowing ocean currents include the Agulhas Current in South East Africa, the Kuroshio Current in East Asia, and the East Australian Current, see Lewis et al. (2011). Ocean Energy, Chapter 6 in IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.

29 Charlier, R. H. & Justus, J. R. (1993).

It is not only the water movements in waves and currents that make the oceans a potential source of renewable power. It is also possible to make use of the temperature difference between warm surface water and cold deep water (ocean thermal energy conversion – OTEC). In the tropics, the sea surface is heated by the solar energy to around 25 degrees, whereas the temperature at 1000 meters depth is around 4 degrees. The theoretical maximum conversion efficiency (the Carnot efficiency) depends on the temperature difference, see Figure 3.3. The technical efficiency is in general less than half of the theoretical. A temperature difference of around 20 degrees would therefore imply an energy conversion efficiency of about 3%.

A recent study based on an ocean general circulation model find a physical potential of 120 000 TWh/yr.[30] Beyond this point, additional plants will reduce the production of other plants due altered water temperatures (compare top down assessments of wind power above). A production on this scale would have major global environmental impacts. At a production of 60 000 TWh/yr it is estimated that global ocean currents and temperatures will be only marginally affected. However, the socio-economic potential is likely to be constrained by local environmental concerns (Chapter 8). In addition, OTEC plants need to be quite close to the demand, to reduce the need for long distance cables in the oceans, and will still require a depth of 1000 meters.[31] The main economic potential is perceived to be in small islands in the Pacific that today rely on expensive energy import. Due to the very large uncertainties involved, we here refrain from trying to estimate technical and socio-economic potentials.

GEOTHERMAL POWER

Larger natural heat gradients than those found in the ocean are accessible for energy harvesting. The heat flow from the interior of the Earth due to radioactive decay (66%) and the slow cooling of the Earth (33%) creates a potential to extract geothermal energy.

The total heat flux through the surface of Earth crust is around 400 000 TWh/yr (Table 3.1), whereof 90 000 TWh/yr through terrestrial surfaces.[32] How much of this that theoretically could be converted to electricity depends on the temperature difference that can be utilised (Figure 3.3). In one assessment the difference between the temperature at the Earth's surface and the temperature of about 800 ˚C at the interface between the crust and the mantle was taken as a basis for estimating a theoretical efficiency of 70%. This would result in a theoretical potential of about 60 000 TWh/yr below the continents (Table 3.2).[33] None of these figures include the potential of 'mining' heat from dry rock. The heat content of the earth crust is in the order of 100 000 times larger than the annual heat flow through the

30 Rajagopalan, K. and Nihous, G.C. (2013). Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model. *Renewable Energy* 50:532-540.

31 On site hydrogen production via electrolysis has been suggested as a means to circumvent limitations related to long distance cables.

32 Stefanson, V. (2005). World Geothermal Assessment, Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April.

33 Hermann, W. A. (2006).

crust. We are not aware of any assessment of the potential and effects of large scale extraction of the slowly replenished heat in dry rock.[34]

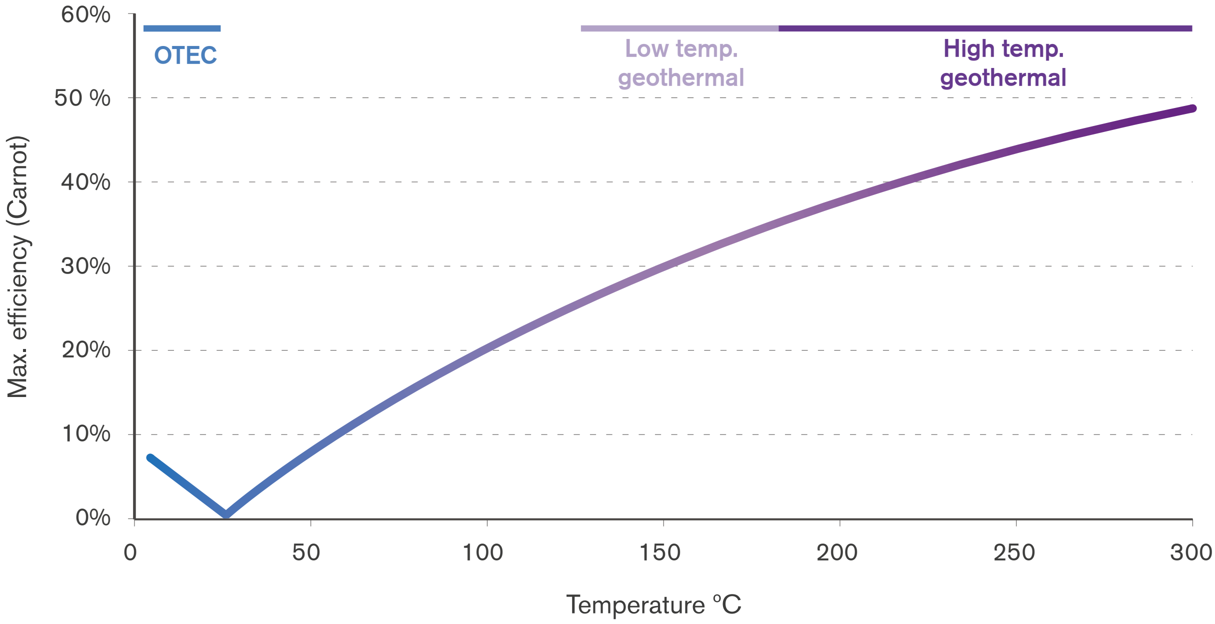

Figure 3.3 Theoretical maximum conversion efficiencies to electricity for different temperature differences (the Carnot efficiency).

Today, geothermal energy is harnessed in specific geological settings utilising geothermal fluids with temperatures of about 120-300°C (Figure 3.3). Based on a relation between the occurrences of volcanoes and identified geothermal resources a global technical potential has been estimated at about 2000 TWh/yr. This could be reduced to 400 TWh/yr with pessimistic assumptions and increased to 10 000 - 20 000 TWh/yr with optimistic assumptions.[35] A country by country estimate found a technical potential of 300 TWh/yr with the technology available in 1999 and 1000 TWh/yr with improved technology. The latter number was taken as an economic potential (until 2050) in the Global Energy Assessment report. [36] Where hydrothermal resources are available the environmental impact is likely to be modest, hence we here apply this number as the socio-economic potential (Table 3.2).

GEOGRAPHICAL AND TEMPORAL DISTRIBUTION

As is evident from Figure 3.1, the geographical variability of the solar power potential is relatively small. The sunnier regions of the world get only about twice as much irradiation as the less sunny regions. While the distribution of wind power is not as even, sufficient wind power resources are available over large areas of the world.

34 Mining of stored heat that is not replenished is by definition not renewable. However, extraction could in principle shift the equilibrium and affect the cooling rate of the Earth, and thereby the rate at which the heat is replenished.
35 Stefanson, V. (2005).
36 Gawell, K. et al. (1999). Preliminary report: Geothermal energy, the potential for clean power from the earth, Geothermal energy association, Washington, USA. Rogner, H.-H. et al. (2012).

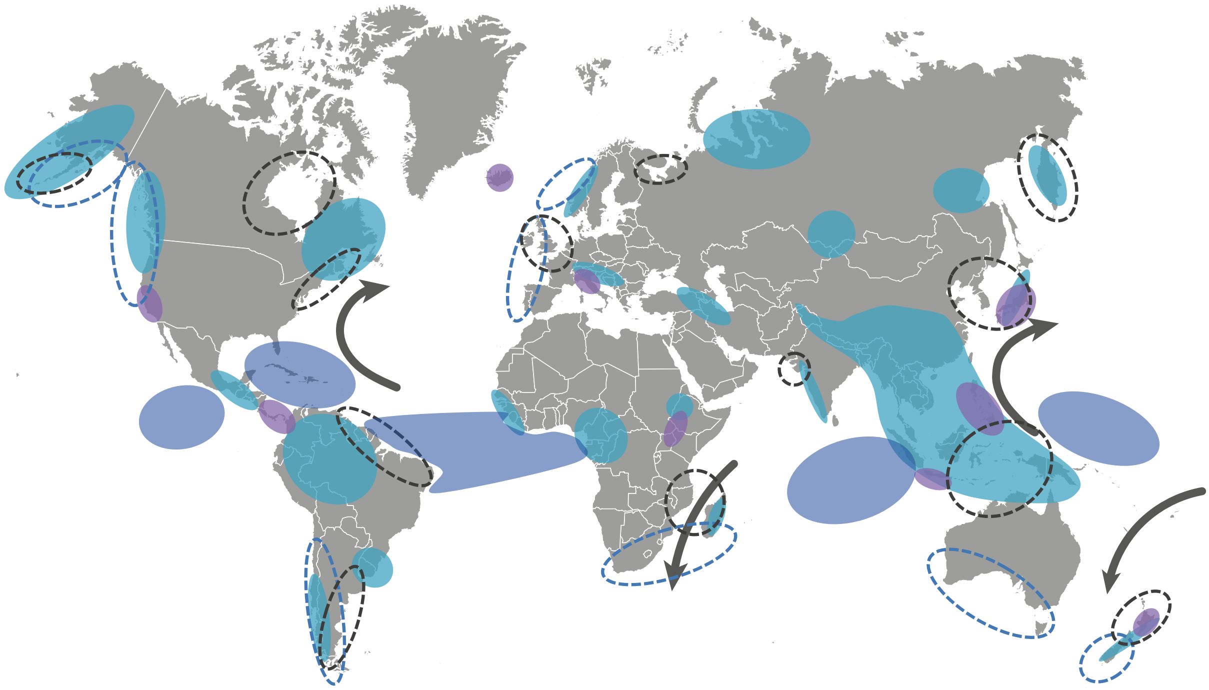

Figure 3.4 Global renewable power hotspots (solar and wind excluded): small-scale and large-scale hydropower (teal), geothermal energy (purple), ocean thermal energy (blue), tidal power (black broken line), wave power (blue broken line) and ocean current power (gray arrows).

In contrast, the geographical concentration of the geothermal resource and of the water power resources is very large. Zones where hot spots exist are depicted in Figure 3.4. While the OTEC resource is in principle is more wide spread over tropical seas, any socio-economic potential will likely be geographically concentrated as well. The implication of this is that even if the global potential of all these resources is relatively small they can all be of local importance.[37] One can view the water (and wind) energy resources ultimately derived from solar energy, as local concentrations of the solar energy influx, with a potential to deliver power at low cost with specific characteristics where available (compare the energy densities in Figure 3.1 and 3.2).

The concentration to specific locations implies that local environmental and social factors will be critical determinants of how much of the technical potentials that will be utilised in the future (Chapter 6 and 8). We can also note that very high percentage of the technical potential of hydro power is already utilised in some countries, e.g. about 70% in Sweden and Norway and almost 90% in Switzerland.

The solar energy inflow varies on different timescales. The night-and-day variation is present everywhere. The seasonal variation is prominent closer to the poles, but hardly noticeable in the sunnier regions closer to the equator. While these variations are fully predictable there is also whether dependent variation on shorter time scales. The wind resource is generally less predictable (see also Chapter 4, 9 and 11).

37 Maps of wave, ocean current and tidal energy intensities are provided in Lewis et al. (2011).

Hydropower with dams is very flexible and can deliver power on demand (see also Chapter 11). Geothermal power and OTEC can deliver a constant flow of electricity. Ocean current, run-of-river hydro and osmotic power will likely have a fairly constant output with some variations over seasons. Tidal power varies with the tidal cycle but is highly predictable. Wave power is variable and less predictable. However, it is less variable and more predicable than wind and some areas have a fairly constant inflow of ocean swell.

CONCLUSION

The answer to the question posed in the chapter heading is clearly yes. While the renewable energy flows currently supply only a fraction of global energy and electricity demand, the technical potential is two orders of magnitude larger than current and anticipated demand. Our attempt to estimate a realistic socio-economic potential indicates that an energy system that can be sustained as long as the sun shines can be several times larger than the current global energy system. It is also evident that a complete replacement of fossil fuels and nuclear energy will fundamentally rely on the direct conversion of solar energy, with wind and hydro power as important complements. While, all the other renewable energy flow resources, most likely, always will remain marginal at the global level, they can indeed be of great local importance due to geographical concentration. Due to differing characteristics in terms of temporal variability and control they may also serve to balance supply and demand of electrical power.

4

HARNESSING ENERGY FLOWS: TECHNOLOGIES FOR RENEWABLE POWER PRODUCTION

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INTRODUCTION

In this chapter, the technologies for renewable power production of today and in the near future will be described and explained. Renewable power production is electric power production without using a fuel that will end some day in the future. In this chapter, as in this book, power production based on renewable fuels (biomass) is excluded (see Systems perspectives on biorefineries).

Some of the technologies such as wind or solar has reached industry mass production in recent years, hydro power has been in operation more than 100 years and others like wave or ocean current power have still some development to do before robust power production units are available.

SOLAR POWER

Solar energy is harnessed today by two main types of technology. Thermal-electric systems, often called concentrating solar power (CSP), collect the light from the sun and convert that thermal energy to electricity through a heat engine, whereas photovoltaic (PV) systems convert the photons from sunlight directly into electricity in a semiconductor device. Although the photovoltaic process is more direct, the overall efficiency (percent of sunlight incident that is converted to electricity) of commercial solar thermal-electric and photovoltaic systems fall in similar ranges (10-30%), with the high end of this range reached for both high concentration PV systems and some CSP systems.

All solar power technologies use electromagnetic radiation from the sun to generate electricity, but if a system optically concentrates the light it collects primarily the direct portion of the radiation, whereas non-concentrating systems (e.g. flat plate PV) can collect both the direct and diffuse components of sunlight (see Chapter 3).

Additionally, since only direct light can be optically concentrated, concentration requires the ability to track the sun so that the collector is always pointing directly at the sun as it moves across the sky, further complicating the system. However, since solar thermal-electric efficiency benefits greatly from generating higher temperatures to drive the heat engines that convert the thermal energy to electricity, concentrating systems are the standard in this arena.

In the case of photovoltaics, there is also a potential, due to the properties of the PV cell material, to increase efficiency and substantially decrease the needed amount of the sometimes expensive photovoltaic material by using concentration, typically with exotic multi-junction high-efficiency solar cells. The economics of concentrating PV (CPV) are not as favourable as in the CSP case, because CPV increases the need for cooling, in addition to the tracking and more complex optics required, and there is typically not as strong an increase in efficiency with concentration as in thermal systems.

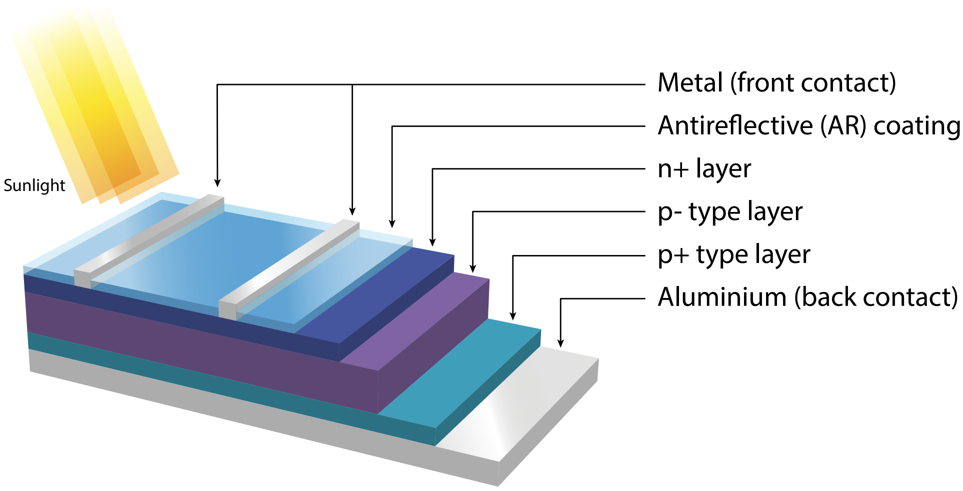

Figure 4.1 A crystalline silicon solar cell.

At the core of photovoltaic technology is the solar cell, or the material that converts the sunlight to electricity. A solar cell is formed at the junction between two semiconductor materials (of which there exists many varieties). Multiple such junctions can be arranged in series (or parallel) that have different abilities to absorb different wavelengths of light (corresponding to different electron band gaps). All of these variations, in the end, affect how much of the sunlight can be converted to electricity, with the goal to develop low-cost materials reaching the theoretical limit of efficiency. For a single junction cell, as shown in Figure 4.1, this efficiency limit is approximately 30%, but increases to 42% for two-junctions, and 48% for three-junctions, with a theoretical limit of 68% achievable with infinite junctions. Under high concentration the corresponding limits are 40% for a single-junction cell, 55% for two-junctions, 63% for three-junctions, and an 86% theoretical limit with infinite junctions.[1]

The PV industry is dominated by silicon cells. Silicon technologies are broadly divided into crystalline cells (single or polycrystalline), which make up over 80% of the world market,[2] and non-crystalline cells (amorphous). Amorphous cells are generally thin-films, meaning a thin layer (about one micrometer) of the semiconductor material is deposited on a base layer. This process reduces cost by reducing the amount of material used in the process, but also decreases the efficiency of the cell compared to crystalline silicon cells. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) cells are other examples of commercial thin film technology. At the top end of the spectrum, in terms of efficiency, are multi-junction cells, the most advanced of which are generally made up of layers of compounds of group III and V elements of the periodic table. A range of other types of cells are under development including dye-sensitised, organic, and quantum dot solar cells.

When talking about systems that convert sunlight to thermal energy and then to electricity, we often use the term "concentrating solar power" (CSP) although, as mentioned above, these systems could also focus the sunlight on PV cells instead of a thermal fluid. The scale of CSP systems is usually very large (i.e. power plant), but smaller systems can also be designed, for example, in remote villages for rural electrification. Solar thermal-electric systems offer the advantages of being suitable for operation on other fuels when the sun is not shining, and can store energy as thermal energy to later be converted to electricity. This method of storing energy thermally is generally less expensive than storing the generated electricity at a later stage (see also Chapter 5 and 12).

The general principle behind solar thermal-electric systems is that a working fluid (usually a molten salt, mineral oil, or water) is heated to high temperatures at the focus of a concentrating solar collector, and the energy from that hot fluid is then used to run a heat engine. The heat engine is usually based on either a Rankine cycle (the same cycle used in most fossil-fuel power plants) or a Stirling cycle.

To get the high temperatures needed to operate heat engines efficiently, solar thermal-electric systems usually use concentrating solar collectors which can produce fluid temperatures from a couple hundred to over a thousand degrees Celsius. These collector systems can generally be categorised as one of four types: Parabolic trough, linear Fresnel, dish engines, or central receivers, as shown in Figure 4.2.

1 De Vos, A. (1980). Detailed balance limit of the efficiency of tandem solar cells. *Journal of Physics D: Applied Physics* 13(5): 839.

2 Masson, G, M et al. (2013). Global market outlook for photovoltaics 2013-2017. *European Photovoltaic Industry Association (EPIA), European Commision May.*

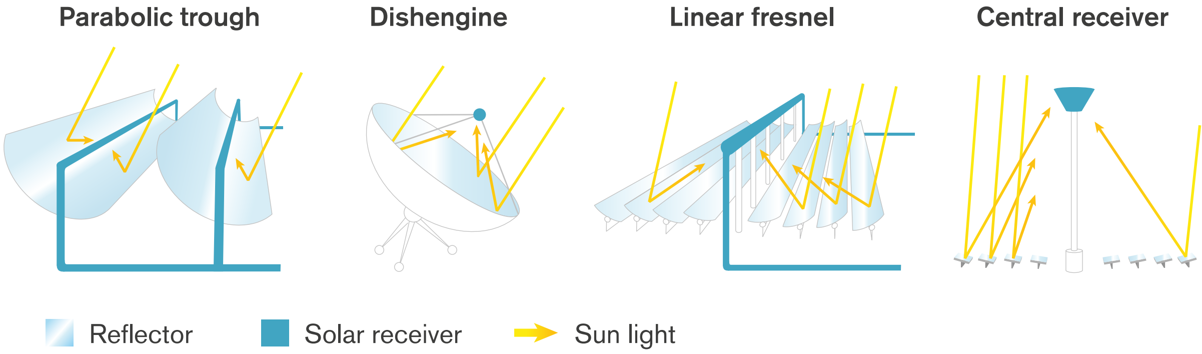

Figure 4.2 Types of CSP (Concentrating Solar Power).

An area of expanding research in the field of solar power is so called hybrid PV-thermal (PVT) systems. These systems combine a thermodynamic heat engine cycle, like in CSP, with a photovoltaic material to boost the overall conversion efficiency of sunlight to electricity. For example, one such system would use an optically selective fluid (e.g. with suspended nanoparticles) running over a photovoltaic material at the focus of a concentrating solar collector. The fluid would mainly absorb those wavelengths of light that were not useful to the PV, thereby allowing the useful wavelengths to hit the PV, while the other wavelengths heat the thermal fluid to high enough temperatures to run an additional heat engine cycle to produce electricity. The overall solar-electric efficiency from such a system could be higher than either a CSP or PV system alone.

The output of all solar power systems varies directly with the amount of sunlight, so is highest during the summer (on the northern hemisphere), tapers off in the winter, and varies depending on seasonal weather patterns. Regions nearer to the equator see less variation and more total production.

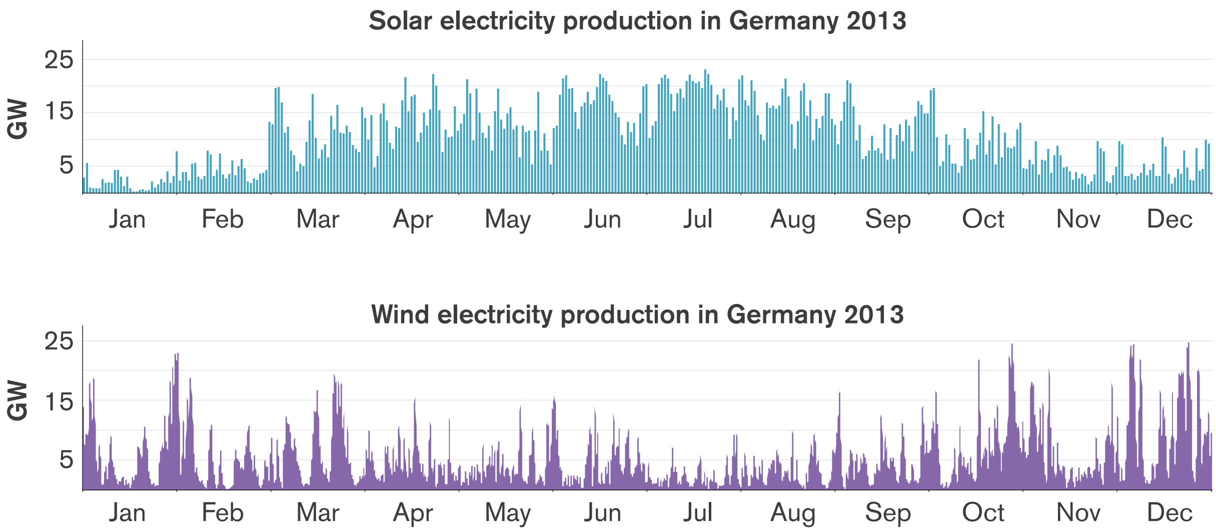

Figure 4.3 Solar electricity production in Germany, 2013 (top) compared to wind electricity production in the same year (bottom). "Electricity production from solar and wind in Germany - Fraunhofer ISE." (2013)

Figure 4.3 shows the total production of solar electricity in Germany in 2013 compared to the corresponding production from wind turbines in that year. Note that the seasonal variation of these technologies makes them good complements for each other, as wind is often stronger in the winter months and solar in the summer months.

As of 2013 PV make up the lion's share of existing solar-electric capacity, with global PV capacity estimated at 140 GW, and thermal-electric at less than 3 GW. The solar electricity production the same year can be estimated at 130-150 TWh.[3] In the last decade, the installed PV capacity has grown, on average, by more than 50% annually.

WIND POWER

Wind power turbines create electrical energy from the kinetic energy in the wind. A wind power plant operates according to following principle: 1) The motion of the wind puts the turbine in motion; 2) a torque is created on the axis connected to the generator; and 3) the generator transforms mechanical energy into electrical energy.

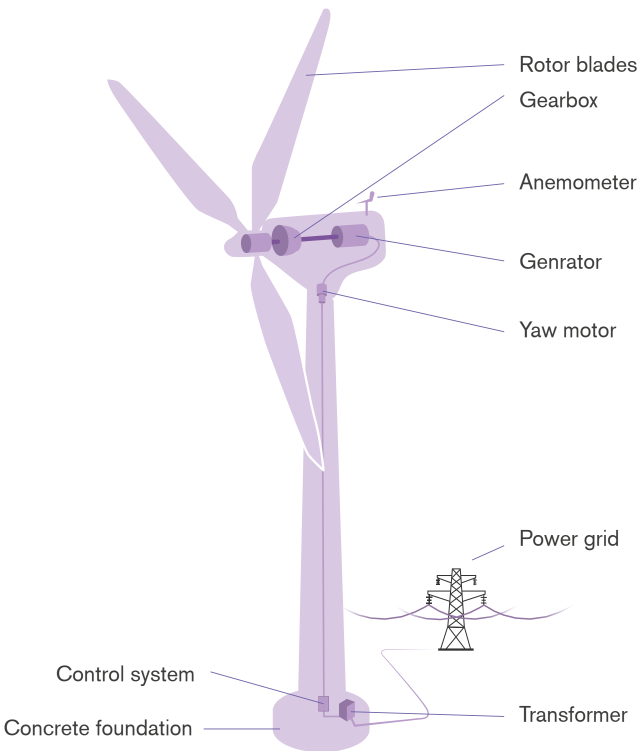

Figure 4.4 Components of a wind power plant.

A wind power plant consists of a number of components, shown in Figure 4.4. The main components are foundation, tower, wind turbine and nacelle. The foundation gives stability to the plant construction. The tower is often created by steel and has the shape of a cone. Some fabricates has concrete as an alternative material for the tower. The nacelle contains gearbox, generator and electrical equipment, and it turns towards the wind direction. There are several ways to design a wind power plant. Size of tower, rotor blades and the electrical system varies between different models.[4]

3 The rapid growth in many different countries with varying insolation makes the estimate uncertain. The estimate is based on BP (2013). BP statistical review of world energy 2013.

4 Wizelius, T. (2002). Vindkraft i teori och praktik, Studentlitteratur.

The kinetic power of the wind is proportional to the density of the air mass and the third power of the wind speed (see Box 4.1). The implication of this is that when the wind speed doubles, the power increases by a factor of eight. Hence, the wind energy resource varies a lot between windy and less windy locations (see Chapter 5).

Box 4.1 Power and tip speed ratio.

The power from a turbine, *P*(W), is calculated from:

$$P = c_p\, P_w = \frac{1}{2}\, c_p\, \rho\, A\, v_w^{\;3}$$

where P_w = kinetic power of the fluid (wind or water current), ρ = density of the fluid (kg/m^3), A = wrapped rotor area (m^2), v_w = undisturbed wind speed (m/s), c_p = efficiency coefficient = 16/27 η, where 16/27 is the theoretical maximum efficiency (the Betz limit) and η = the efficiency of the turbine, c_p is usually 0.4 – 0.5 for wind turbines.

The tip speed ratio λ, measures of how fast the blades rotate compared to the speed of the fluid (wind or water)

$$\lambda = \frac{v_b}{v_w} = \frac{\omega r}{v_w}$$

where v_b = tip speed of the blades (m/s), r = radius of the rotor (m), and ω = angular velocity (rad/s).

When a wind turbine is designed, the tip speed ratio is an important parameter. It is a measure of how fast the blades rotate compared to the wind speed (Box 4.1). If the wind turbine rotates too slowly, most of the wind will pass the rotor without hitting the blades. On the other hand, if the rotor speed is too fast, the wind will have a hard time passing the rotor, since the rotating blades will act like a wall against the wind. Because of this, the wind turbine is designed according to an optimal value of the tip speed ratio, to extract a maximum amount of energy. The theoretical maximum efficiency of a turbine, the Betz limit, is about 59% (or exactly 16/27).

For technical reasons, each power plant has maximum power output, i.e. it cannot make use of the all the energy of wind speeds above a rated speed. Figure 4.5 shows the theoretical wind power curve and a curve measured from Chalmers wind power plant on the island of Hönö. The measured values initially follow the theoretical curve, but as the rated wind speed is approached, the measured power output stabilises at a constant value. At this point, the turbine, not the available wind energy, limits the power output.

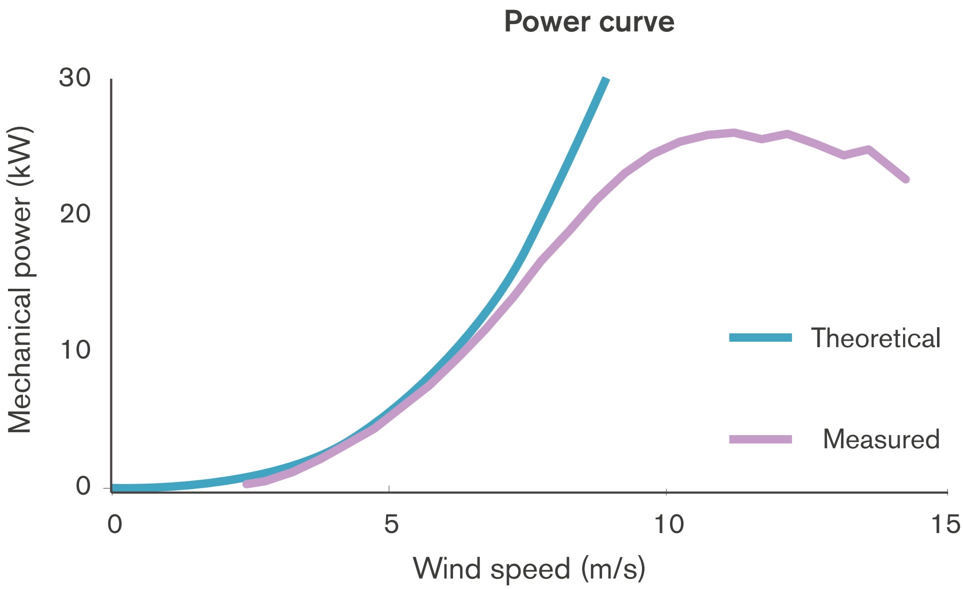

Figure 4.5 Theoretical and measured power curve from Chalmers wind power plant on the island of Hönö, Sweden.

There are mainly two types of wind power plants, vertical axis wind turbines, VAWT, and horizontal axis wind turbines, HAWT. In the VAWT, the axis between the generator and turbine is vertical to the ground, and in the HAWT it is horizontal to the ground. The HAWT dominates the wind power market today. Figure 4.6 shows one traditional (A) and two modern (B and D) HAWTs, and one VAWT (C), and their performance profiles.

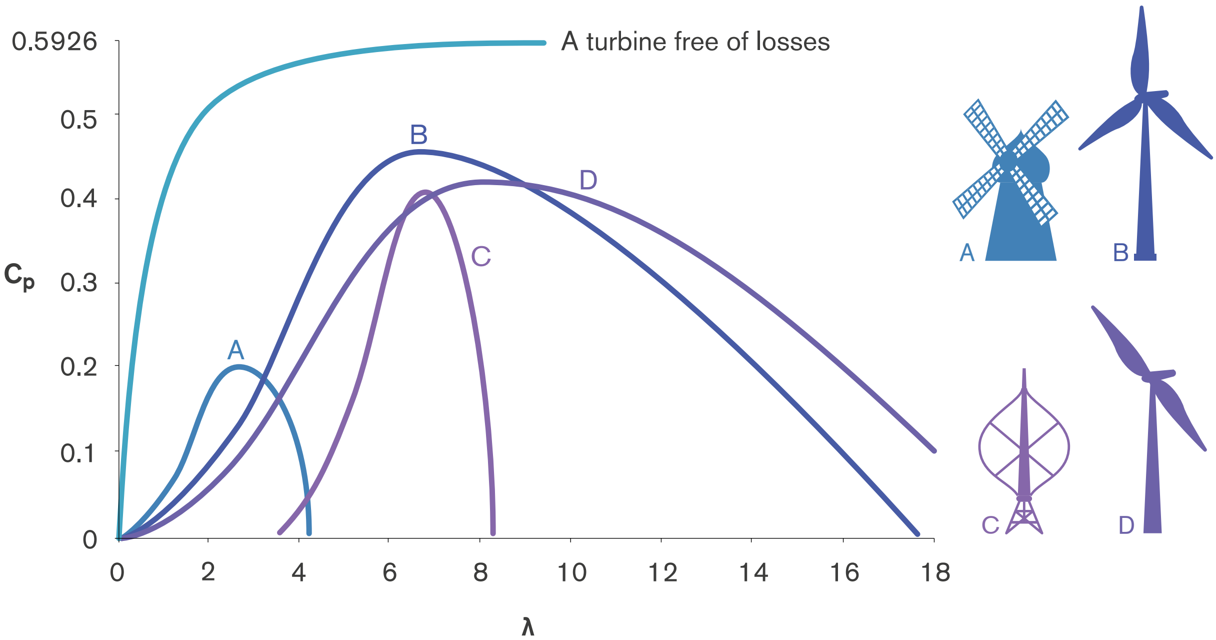

Figure 4.6 Different types of wind turbines.

At the end of 2013, the accumulated wind power installation worldwide was 310 GW and the electricity production in 2012 was about 500 TWh.[5] The installed

5 GWEC (2014). Global installed wind power capacity in 2013 - Regional Distribution, Global Wind Energy Council; BP (2013). BP statistical review.

capacity has on average grown by about 25% annually over the last three decades. In the last decade, the European offshore market has grown rapidly, from a few MWs to an installed capacity of more than 6 GW in 2013.[6]

HYDRO POWER

Hydro power, originating from the early civilizations millennia ago, exploits the potential energy of water precipitated on land at altitudes higher than sea level by forcing water from rivers or reservoirs through turbines. The available amount of energy is dependent on water flow (m^3/s) and the head (m) (water level difference). Historically, the mechanical energy was used directly for milling and other machinery. Today, generators convert the energy into electricity.

Several different turbine designs are used. Two common turbines are the Francis turbine and the Kaplan turbine where the former is the most common for high-head systems and the latter is typically used in low-head systems. Hydropower schemes can be of different types: *Run-of-river schemes* have turbines installed directly in a river, or have pipes leading water from a river through an adjacent turbine installation thus harvesting energy from the natural flow without options for energy storage. *Storage schemes* have a dam which impounds water and turbines installed in the dam wall, hereby partly controlling the temporal availability of the energy resource. *Pumped-storage schemes* have several interconnected reservoirs so that water can be pumped from lower to higher reservoirs when electricity demand is low, hereby allowing for a high control of the temporal availability of the energy resource.

The different schemes vary in their ability of storing energy and thereby optimising the selling price. Storage- and pumped storage schemes can be useful base supply in electric grids where power is saved for peak load periods (see Chapter 11), while run-off-river schemes, which are smaller, have the advantages of simple installation, lower environmental impacts and higher geographical availability. Although large-scale hydropower contributes with the vast majority of generated power, small-scale hydropower is regarded increasingly important for remote area power supply in many countries.[7]

Hydropower production has grown almost linearly over four decades, from 1000 TWh per year in the 1960s to 3700 TWh in 2012. Since 2000, its share of world electricity production has remained at about 16%.[8]

TIDAL POWER

Tidal power comprises both tidal barrages and tidal current turbines. Barrages capture the tidal wave inside large enclosures that are open when the tide rises and closes at high tide. With tidal withdrawal, at ebb, a head is created between the water trapped inside the barrage and the natural sea level outside the barrage. Electricity is generated when the water levels are allowed to even out through low-head turbines.

6 EWEA (2014). The European offshore wind industry - key trends and statistics 2013, European Wind Energy Association. See also Chapter 15.

7 Kumar, A. et al. (2011) Hydropower. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (eds O. Edenhofer, et al.), pp. 437-496. Cambridge University Press, Cambridge and New York.

8 BP (2013). BP statistical review.

Tidal barrages can operate through *one-way mode*, where electricity is only produced during ebb, or *two-way mode*, where electricity is generated during both flood and ebb.[9] Tidal barrages are normally constructed across natural bays or river inlets in order to minimise the length and cost of the barrage. Modern tidal barrages may also come to be constructed on offshore banks (called tidal lagoons). Tidal barrages are based on conventional hydropower technology and can be used both for supplying local needs through small tidal ponds and for large scale power production.[10]

Tidal barrage technology is proven since more than 50 years but only a handful of large barrages have been installed. The most well-known being La Rance power station (240 MW) in France but the technology is used also in e.g. South Korea, China, Canada and Russia. A very large tidal barrage is now under appraisal in the Severn Estuary, UK.[11] A mean tidal range of 5 m is often thought to be required for tidal barrages to be economically feasible, but with modern low-head turbines also lower tides may be of interest.[12] Tidal barrages imply modification of the natural tidal regime, inevitably affecting the local environment. The environmental impact of tidal barrages has long been considered a major constraint to expansion of the technology (Chapter 8).

Tidal current turbines utilises energy from the fast-flowing currents that develop where the tidal wave passes through narrow straits or bends around peninsulas. A large number of technical solutions for tidal current power are currently under development. Electricity is generated through submerged turbines typically driven by large *horizontal-axis rotors*, much looking like underwater wind power plants, or small *vertical-axis rotors* mounted in grid-like constructions. Some designs are also based on *oscillating hydrofoils.*[13] On smaller turbines the water flow over rotors can be enhanced by ducting shrouds.

As with wind power and wave power, tidal current power is based on relatively small units (<2 MW) and meant for deployment in arrays. Most of these modern devices are open-flow tidal current turbines targeting tidal currents with water speeds around 2-4 m/s. The energetic currents also imply harsh conditions and rise high demand on marine engineering. Nevertheless, several full-scale devices have recently been installed and the technology is often believed to stand a good chance of becoming locally important in the near future.[14]

The tidal resource is dependent on the tidal range (m) which varies among locations due to landmass positioning and local bathymetry. Fast-flowing currents are rare and tidal current power is therefore particularly site specific (see Chapter

9 Charlier, R.H. (2003) Sustainable co-generation from the tides: A review. Renewable and Sustainable Energy Reviews, 7:187-213.

10 Charlier, R.H. and Justus, J.R. (1993). Ocean Energies - Environmental, Economic and Technological Aspects of Alternative Power Sources. Elsevier.

11 Xia, J. et al. (2010). Impact of different tidal renewable energy projects on the hydrodynamic processes in the Severn Estuary, UK. *Ocean Modelling*, 32:86-104.

12 Liu, L. et al. (2011). The development and application practice of neglected tidal energy in China. Renewable and Sustainable *Energy Reviews*, 15:1089-1097.

13 Khan, J. and Bhuyan, G. (2009). Ocean Energy: Global Technology Development Status. International Energy Agency.

14 Bahaj, A.S. (2011). Generating electricity from the oceans. Renewable and Sustainable Energy Reviews, 15:3399-3416; Esteban, M. and Leary, D. (2012). Current developments and future prospects of offshore wind and ocean energy. *Applied Energy*, 90:128-136.

3). The tidal period is 24 h 50 min and the tide rises and falls one (diurnal tides) or two (semi-diurnal tides) times per day. In addition, the magnitude of tides increases two times per month (spring tides) as the gravitational force of the sun complements the force of the moon. The tidal power output is therefore variable over both hours and weeks, unlike the phase of human demand which typically has a diurnal period of 24 h, sometimes in addition to an annual period. By tidal barrages this can partly be solved by dividing the barrage into different basins so that the outflow is regulated and at least the diurnal variation is reduced. The output of tidal current turbines cannot be regulated and power remains variable but highly predictable.

OCEAN CURRENT POWER

Ocean current power, or ocean current energy conversion, basically works under similar principles as tidal current power, with turbines capturing the energy of the flow. However, due to the low energy density of ocean currents the power devices either have to be very large or particularly ingenious in the design (the power in stream is proportional to the third power of the water speed, see Box 4.1 and Figure 3.2). As an example of the former, it has previously been suggested to extract power from the Florida Current by installing arrays of turbines with rotor diameters exceeding 100 m.[15] A modern example of the latter is the Deep Green prototype, currently being developed by the Swedish firm Minesto. The Deep Green consists of an underwater kite equipped by a smaller rotor and turbine. As the kite is swept in circles by the current the rotor experience an increased water flow, enhancing the energy density by a factor of ten. Ocean current power devices are still in early development and it is not known whether marine fauna will be able to avoid collision with its moving components. Thus, both costs and environmental feasibility of this power source remain very uncertain (Chapter 8).

WAVE POWER

Wave power uses wind-driven surface waves to generate electricity. The many currently developing technical solutions can be classified as *oscillating water column systems* where waves pressurise air chambers and spin turbines, *absorber systems* where a buoy attached to the seabed is dragged up and down by the waves in order to spin turbines or drag pistons through linear generators, *overtopping systems* where waves force water into an elevated reservoir which is emptied through low-head turbines, *inverted pendulum systems* where waves force an oscillator to move back and forth and pressurise fluids to drive generators, or *elongated attenuators* (interconnected elongated floaters) where the wave motions pressurise hydraulics connected to internal generators.[16]

Wave power devices can be shore-based, installed in shallow water, or anchored in deeper water. Floating wave power units are small (<1 MW) but intended for array deployment. As a general indicator wave power devices harvest about a fifth of the incoming wave energy and some devices are more generalist than other in the capturing of variable frequencies of waves. The power output is variable and

15 Charlier, R.H. and Justus, J.R. (1993).

16 Thomas, G. (2008). The Theory Behind the Conversion of Ocean Wave Energy: a Review. Ocean Wave Energy - Current Status and Future Perspectives (ed. J. Cruz), pp. 41-91. Springer, Heidelberg; Khan, J. and Bhuyan, G. (2009) Ocean Energy: Global Technology Development Status. International Energy Agency.

undergoes both seasonal and daily changes, but is typically less variable and more predictable than wind power.[17] Long-distance waves (swell), which characterise tropical oceans, even out much of the short-term variation and thus, wave power around tropical islands can be particularly suitable. A common problem for wave power systems, and particularly for offshore devices, is to be sensitive enough to efficiently utilise common waves and at the same time be robust enough to withstand the rare but powerful extreme waves. Environmental impacts of wave power can be expected to be limited unless a high proportion of the incoming wave energy is absorbed by the power plants (Chapter 8).

OCEAN THERMAL ENERGY CONVERSION

Ocean thermal energy conversion (OTEC) utilises the temperature difference between warm surface water and cold deep sea water using heat engine technology.[18] Surface water and deep sea water are collected from the ocean via large diameter pipes and then released back to the ocean or partly utilised as freshwater. Electricity can be generated using *open-cycle*, *closed-cycle* or *hybrid* designs.

In an open-cycle OTEC warm surface water is vaporised in low pressure chambers and used to drive turbines before it is re-condensed by the cold deep sea water. In a closed-cycle OTEC warm surface water heats up a working fluid that vaporises and drives turbines before it is re-condensed by the cold deep sea water and recycled in the process. In the hybrid design warm surface water is vaporised like in the open-cycle design and is then used to vaporise a working fluid which in turn drives turbines. In the open-cycle and hybrid cycle designs, freshwater is produced as a by-product. This can be an important additional value where water for consumption or irrigation is scarce. For instance, a small OTEC plant has been installed in India with the sole purpose of producing freshwater[19] and a full scale 100 MW OTEC could produce freshwater enough for a larger city.

OTEC power plants can be installed on land or offshore as ship-like constructions. Due to the requirement of massive amounts of seawater, only large scale plants can become economically viable. By adding solar heaters to warm up the surface water the efficiency of the process can be improved.[20] The OTEC resource is determined by water temperature differences (Figure 3.3 and 3.4) and its availability, which in the case of land-based OTEC is determined by the distance between shore and deep sea water (1000 m depth is often assumed to be enough). As the heating and currents are relatively constant, OTEC power production is predictable although it may vary slightly over seasons.[21] The OTEC principles where explored with several pilot plants already in the mid-20th century, so the technical principles are not new. Its implementation has been haltered due to high capital

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17 Charlier, R.H. and Justus, J.R. (1993).

18 Krock, H. (2010). Ocean Thermal Energy Conversion. 2010 Survey of Energy Resources (ed. P. Gadonneix), pp. 588-602. World Energy Council, London; Magesh, R. (2010). OTEC Technology - A World of Clean Energy and Water. Proceedings of the World Congress on Engineering. London.

19 Bhuyan, G.S. (2008). Harnessing the Power of the Oceans. International Energy Agency OPEN Energy Technology Bulletin, 1-6.

20 Straatman, P.J.T. and van Sark, W.G.J.H.M. (2008). A new hybrid ocean thermal energy conversion-Offshore solar pond (OTEC-OSP) design: A cost optimization approach. *Solar Energy*, 82:520-527.

21 Vega, L.A. (2011). Hawaii National Marine Renewable Energy Center.

costs of construction, however, a small OTEC plant is now under construction off the coast in the French island of Martinique. The environmental impact could be considerable (Chapter 3 and 8).

GEOTHERMAL POWER

Geothermal power utilises the heat produced within the earth in order to generate power, in contrast to most other forms of renewable power for which the primary energy source is the sun (see Chapter 3 and Table 3.1).

There are several geothermal resources that could be utilised as heat sources. However, today hydrothermal sources in the form of vapour and hot water at depths up to a few kilometres are the only commercially used sources. In these, water is used as an energy carrier, moving energy from the Earth's interior to the surface. Such resources are primarily created by rain water which percolates down to areas of permeable heated rock, there the water is heated acting as an energy reservoir. On top of the reservoir there needs to be a cap rock, i.e. an impermeable rock that prevent vapour from rising to the surface. In order to utilise the energy, wells are drilled to the reservoirs and through these the hot water or vapour rises to the surface.

At the surface, the heat energy is used to generate electricity and the water, now at a lower temperature, is then injected back into the reservoir. Depending on water temperature of the field three different methods are used to generate electricity: flash-steam, dry-steam and binary cycles. All of these have capacity factors of up to 0.9 (new plants) with an average of 0.75 and are thus able to act as base load plants.[22] The size of a power plant can vary between 0.1 MW and 120 MW.[23]

The most common type is the flash steam. For such cycles the fluid from the well is used as working fluid in a steam cycle. In the process pressurised water rises from the well and as the pressure drops the water eventually flashes into steam. The steam and hot water are then separated and the steam is used to drive a steam turbine. Due to the prevalence of corrosive gases in the steam the relatively low temperature, resulting in water droplets being formed, the turbine needs to be both corrosion and erosion resistant, and therefore more costly than ordinary turbines.

Dry-steam plants are used in areas which can produce dry superheated steam as a source. This removes the need for a flash process in order to separate liquid and vapour, resulting in a less complex and thereby cheaper plant. Steam is instead fed to a particulate remover and then directly to the turbine

22 Goldstien, B. et al. (2011). Special Report on Renewable Energy Sources and Climate Change Mitigation, Geothermal Energy, IPCC; IEA-GIA (2012). Trends in geothermal applications, Survey Report on Geothermal Utilization and Development in IEA-GIA Member Countries in 2010.
23 DiPippo, R. (2012). Geothermal Power Plants - Principles, Applications, Case Studies and Environmental Impact, Third Edition.

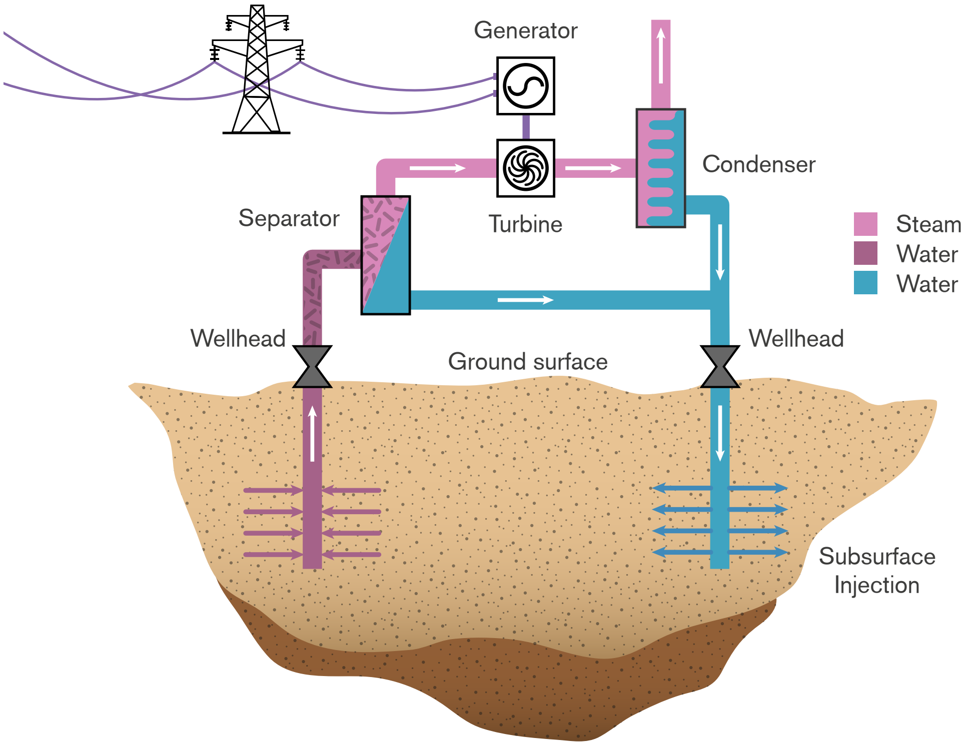

Figure 4.8. Principal schematic of a flash steam plant

For temperatures below 150°C it becomes economically difficult to use a flash process to convert the heat to electricity. Instead a binary cycle, typically an organic Rankine cycle, is used in which a separate working fluid is heat exchanged with the fluid from the well and cycled in the power plant. In such a plant a pump is used to bring the water to the surface and to keep it pressurised enough to remain a liquid. The water is then heat exchanged with the working fluid with a low boiling point. The vapour is then fed to a turbine, condensed and recirculated to the heat exchanger. The water from the well is injected back into the reservoir after the heat exchanger. There are also more complex forms of binary plants as well as combined binary and flash steam plants.

The installed capacity of geothermal power plants has increased linearly since the 1970s and reached 12 GW in 2013 with an expected annual production of 70-80 TWh.[24]

CONCLUDING REMARKS

The electric power production of the world of today is dominated by coal and gas. As described in Chapter 2, there is an urgent need to transition to renewable power. Renewable power plants are different and come in many forms, rely on a range of resources and use a variety of conversion technologies. Some rely on knowledge fields already mainstream in the energy sector, such as the thermodynamic cycles in solar thermal electric and geothermal power plants, others draw on similar physical principles while applied in different environments, such as turbines rotating in air or water, while yet others, such as solar cells, bring in

24 GEA (2013). 2013 Geothermal power: International market overview, Geothermal Energy Association.

the domains of semiconductor electronics and nanotechnology. There are vast opportunities to capture the energy flows that every second pass by, but it will require combination of knowledge fields, engineering ingenuity, entrepreneurial experimentation and continuous investment.

The maturity of the technologies differs widely. While some, like many ocean energy technologies remain to be extensively tested, hydro power has grown steadily over more than a century. In the last two decades, wind and solar PV has grown exponentially, initially from low levels, but now reaching several percent of the electricity supply in many countries. However, as shown in Chapter 3, all renewable power technologies are far from their ultimate potentials, and as shown in the rest of this book, there are many obstacles yet to overcome, related to compatibility with existing technical systems, environmental concerns, economic competitiveness and political power.

5

GRID AND STORAGE

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INTRODUCTION

Large scale introduction of renewables will change the requirements on the electrical grid. The grid will need to handle electricity production at new locations and the variation in time of electricity generation will change as well (see Chapter 4 and 9). Increased variations in power flow, both in amplitude and direction, will also require new types of control and protection of the grid.

The intermittent behaviour of the major renewables, i.e. solar and wind, requires either complementary power sources that can balance power supply (Chapter 11), a shift in energy demand (Chapter 10) or deployment of electrical storage. Storage can also limit or delay the need for grid extension and reinforcement and help solving control and protection issues.

There is a wide range of storage technologies and the choice of technology is dependent on which problem to solve, and in many cases, what resources are locally available. Figure 5.1 indicates discharge time and typical power capacity per unit for a range of storage technologies. Technologies that store a large amount of energy for long a time are suitable for shifting energy supply in time and thereby reducing the need for grid extension; technologies with a short response time can be used to mitigate power quality problems. One can note that for stationary applications like energy storage systems connected to the grid, weight, and in most cases also volume, are of the less importance, as compared to energy storage in vehicles (see Systems perspectives on Electromobility). Therefore alternatives like pumped hydro and compressed air are commonly applied for large-scale and long-term (hours to days) energy storage. However, pumped hydro has geographical requirements and technical and economical limitations that limits its application.

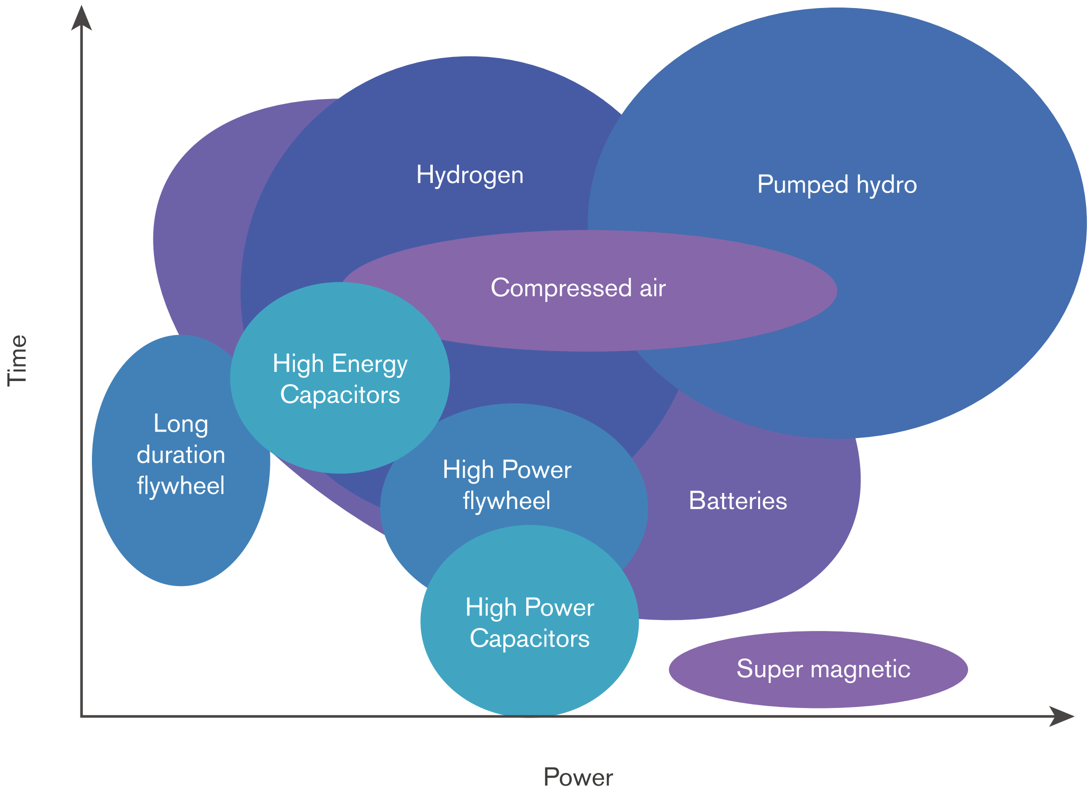

Figure 5.1 Discharge time and different available capacity rates for storage technologies. The figure is only indicative. The time scale is logarithmic from seconds to months and the power scale is logarithmic from kW to GW.

Off-grid systems are systems for an isolated area like an island or a village or even a house or a single device. These are mainly used where connection to the national, or local grids, are too expensive. The interest in off-grid systems has increased due to the decrease in cost of small-scale renewables, like solar panels and small wind turbines. To balance demand and supply in an off-grid system a combination of several energy sources is beneficial but in most cases energy storage systems are required.

This chapter contains a short overview of the basic functions of grids for renewables as well as a short description of current and future technologies for electricity storage. The chapter also includes a brief discussion on more unconventional ways of looking at electricity storage.

THE ELECTRICAL GRID AND CONNECTION OF RENEWABLES

A grid is a network used for transmission and distribution of electricity. The grid can be divided into three levels: the transmission, subtransmission and local grid. The transmission grid is the highways of electricity used to transmit large amount of power long distances, e.g. to supply one part of the country with electricity produced in another part. The transmission grid uses high voltage (> 200 kV) to limit losses, which makes all installations very costly and requires a lot of space. The transmission grid is normally built and operated in a way that power can take other ways through the system during maintenance or if something goes wrong (the grid is meshed). This redundancy is important since a lot of people will be affected if the transmission system goes out of operation. Only very large production units (hundreds of MW) are connected to the grid at this level.

The subtransmission grid is used to distribute electricity in a part of a country. Power is distributed in a meshed grid at lower voltage then in the transmission grid (70 - 130 kV) to limit the cost of installation and the space required. The redundancy at this level is the same as at the transmission level. Large production units (tens of MW) and very large consumers (above tens of MW) are connected at this level.

The local grid consists of two parts: a medium voltage part (10 - 30 kV) and a low voltage part (110 – 400 V). The medium voltage grid is used to distribute electricity from the nodes of the subtransmission grid to large consumers and production units (100 kW to a few MW). The medium voltage grid is normally built in rings but operated radially. This allows the system to be reconnected in a different configuration after faults, however, not automatically. This gives a redundancy but costumers and productions units will experience short interruptions. For planned outages, reconnection can normally be done to avoid even short interruptions. The low voltage system is used for distribution of electricity for blocks and small neighborhoods. At this levels, single household consumers, small business consumers and small production units (< 100 kW) are connected.

The above mentioned grids are interconnected at a substation that both handle the voltage transformation between the levels and works as nodes in the grids. In the substations also control and protection units are placed. Normally it is the capacity of the transformation that is the limiting factor at a substation.

The figures indicating what capacities of production and consumption units can be connected at the different grid levels are only indicative and highly dependent on the local conditions of the grid or even on individual lines and transformers. When planning for connecting renewables to the grid also the direction of the power is important and the local balance between demand and supply. From this perspective, renewables should be connected at as low voltage level as possible to use of the grid efficiently and avoid jeopardising the reliability of larger parts of the system.

From the perspective of efficient grid operation, there are positive as well as negative effects of high penetration of renewables. For the introduction of renewables, the existing grid is mainly beneficial. However, as renewable electricity production expands, fundamental changes in the system will be required.

The main idea used today when dimensioning the grid is that the size of the grid connection is based on the installed production capacity, independently of the number of utilisation hours. This means that there should always be grid capacity available for full electricity production even though there is not always production available. To reduce investments in new power lines and substations and thereby reduce cost and environmental intrusion, production limitations (curtailment), or distributed storage systems could be used in future (see also Chapter 9-10 and 12).

To reduce losses in the grid, renewables should also be connected (normally also located) as close as possible to consumption. The losses in the grid are highly dependent on the geographical distribution of production and consumption. In Sweden, which has an oblong system, with much production in the north and the main part of the consumption in the south, the total losses in the system are up to 10 %. A large number of small scale renewables could utilise the current grid more efficiently, and may even reduce overall losses, if they are located close to consumers.

Since all parts of the grid are interconnected, all things will affect each other, and since the functioning of the grid is critical to society, there are a number of requirements on all grid connections. The requirements on renewables are depending on where in the system they will be connected but also on the size of the installation. Renewables connected to the transmission and sub transmission grid will have large impact of the national grid and therefore national regulation is set to secure operation of the grid. The national regulations are normally called grid codes and set by the transmission system operator. There might also be additional requirement to secure local compatibility.

Renewables connected to the local grids are of less importance to operation of the national grid. Some parts of the grid codes still apply but the local grid codes are more important that emphasise the compatibility with nearby installations, both costumers and other production units.

In general, the cost of expanding the grid shall be paid by the one who require an upgrade, but on the other hand, if capacity is available no connection cost will be charged. Under certain circumstances, this will cause a threshold effect. Someone has to take a large initial capital investment while the following will benefit from it, since most often it is not possible to make an extension of the system that will fit only the need for the one who wishes to connect. In addition, upgrades far away from the installation may be needed to maintain the possibility to use a meshed grid and to keep the desired level of redundancy. This could make the threshold even higher.

STORAGE AS A COMPLEMENT TO RENEWABLES

The intermittent behaviour of the major renewables may create problems when they replace production with more constant generation (see Chapter 3, 4, 9 and 11). A major concern is to what extent it is possible to compensate for frequency changes in the grid fast enough (Figure 9.1). This can, however, be solved by the fast reactions of some storage technologies (Figure 5.1).

Storage installations can also be used reduce, or delay, the need for grid extensions. Energy shift electricity storage localised close to bottlenecks in the grid can be charged when there is a risk of overload and discharge when there are free capacity in the bottleneck. With very high levels of renewables, storage technologies could also be used shift energy supply over longer time frames (weeks and months).

Electricity storage can also be used as an uninterruptable power source that will supply a load when the grid is out of operation. Since many of the storage technologies require a frequency converter to charge and discharge they can serve other purposes too. The converters can be used for power quality problem mitigation like voltage control, harmonics and voltage dip mitigation. By production or consumption of reactive power they may also reduce losses in the grid.

STORAGE TECHNOLOGIES

There is a variety of technologies available today and some are more useful as complement to renewables and grid support then others. In these applications, cost, reliability and lifetime are more important the weight. Normally, volume is not a limiting factor for grid connected electricity storage either, but in some urban or in-house applications it might be. Therefore the low cost alternatives like pumped hydro and compressed air are commonly applied for large-scale and long-term (hours to days) energy storage.

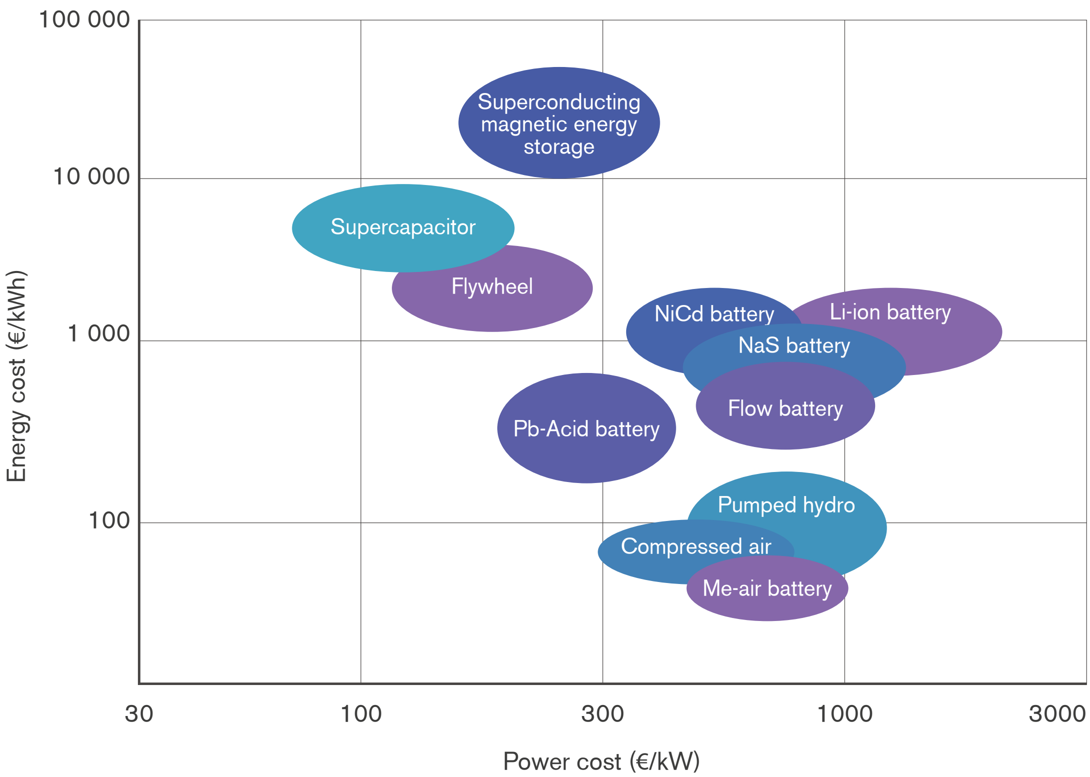

Figure 5.2 Costs of different energy storage technologies.

PUMPED HYDRO STORAGE

The basic principle of pumped hydro energy storage (PHES) is to store electricity by pumping up water to a reservoir, convert it to hydraulic potential energy, and then release the power when needed.

There are two main types of PHES: pure PHES, also known as closed-loop or off-stream PHES, and pump-back PHES. The pure PHES is a technology based on a closed water system where the same water is reused in the system continuously. A sketch of the basic principle for a pure PHES can be seen in Figure 5.3.

A pump-back PHES is a combination of a conventional hydropower system with a natural flow through the system where the PHES utilises the capacity in the dam and the turbine.

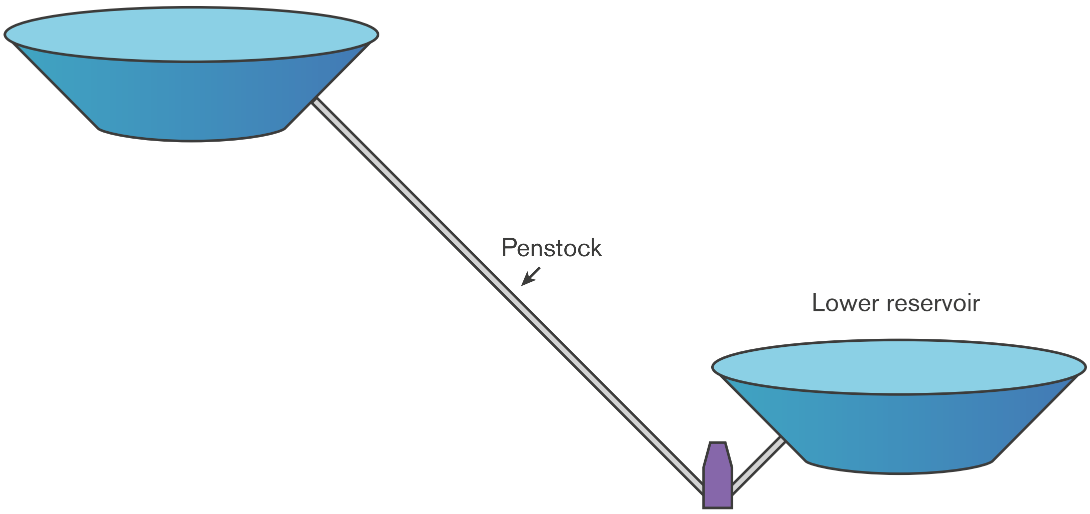

Figure 5.3 Basic principle for pure pumped hydro energy storage

PHES is a mature technology and is currently the only commercially proven energy storage technology for large scale (>100 MW) storage. Today more than 300 plants are installed worldwide with a total installed capacity of more than 95 GW. The dominant users of PHES are Japan and USA, with approximately 50 % of the installed capacity worldwide. The round trip efficiency is about 60-75%.

PHES was mainly installed during the 1960s to 1980s as an energy reserve due to the increased use of nuclear power. The PHES were installed for control and to allow optimum use of the nuclear power reactors. The installation rate has now declined since the best locations have already been exploited. However, the interest of new installations is expected to increase with the growth of intermittent renewable power. PHES are suitable for services like energy shift and frequency stabilisation.[1]

The major disadvantage of PHES is the requirement for special site conditions. It requires two large reservoirs, except for seawater systems that only require the upper basin but then instead needs to be close to a shore with an elevation difference. The environmental effects are believed to be similar to normal hydro-power plant, but the water level in the reservoir(s) will change more drastically (see Chapter 6).

There is an ongoing development of PHES technology. By varying the speed of the pump, the PHES can be used for control purposes also during pumping and the efficiency could increase. The expected increase in installation cost is

1 Deane, J.P. et al. (2010). Techno-economic review of existing and new pumped hydro energy storage plant, Renewable and Sustainable Energy Reviews, 14: 1293-1302.

approximately 5%. Furthermore, a change to a multiblade turbine pump runner has shown to increase the efficiency by 4%. In Japan, tests have also been conducted with sea-water PHES that utilises sea water and is expected to lower the civil construction costs and increase the number of available sites; however, there is a concern for increased corrosion due to the salinity.

COMPRESSED AIR STORAGE

Compressed Air Energy Storage (CAES) is a technology to store energy as compressed air in large volume. It is suitable for balance energy daily. In terms of air storage approaches, CAES can be divided into underground air storage and above-ground air storage.

The underground system uses a compressor to pressurise air and pump it into underground geological formations like caverns in abandoned salt mines, see Figure 5.4.

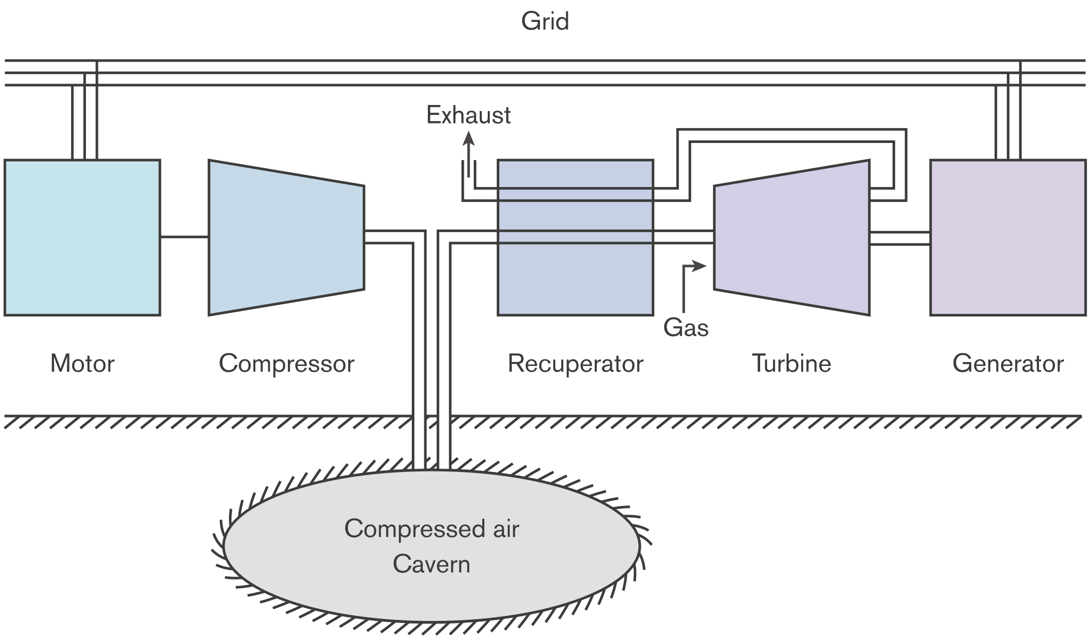

Figure 5.4 Large-scale compressed air energy storage (underground)

Air is compressed and pumped into the caverns when energy demand is low. The pressurised air is then released through a recuperator (a kind of heat exchanger) and heated with small quantities of natural gas or biogas to drive a gas turbine to provide electric power to the grid through a generator when needed.[2] This technology is mainly used for large-scale energy storage with a power capacity of 100-300 MW. The appeal of underground CAES is that it is cost-effective for large installations. But the suitable locations with right size cavern can be hard to find. The first commercial CAES was installed in Huntorf, Germany in 1978 with a power capacity of 290 MW for three hours.[3] Another plant with 110 MW power capacity and duration of 26 hours was built in 1991 in Mcintosh, Alabama, USA. Both plants use old salt caverns.

2 Vadasz, P. (2009). Compressed air energy storage. Energy Storage System – Vol. I. Encyclopedia of Life Support Systems (EOLSS).

3 Crotogino, F., et al. (2001). Huntorf CAES: More than 20 Years of Successful Operation. SMRI Spring Meeting, Orlando, Florida, 351-362.

Another CAES technology relies on above ground air storage. Pressurised air is stored in man-made high-pressure containers, tanks or pipes. The storage can be placed where needed, for example, close to wind or solar farms.[4] CEAS may thus offer an alternative to upgrading lines allowing for a more even transmission of power. An optimal configuration of an above ground CAES is currently believed to have a capacity of 10-30 MW and a storage duration time of 4-6 hours. An above ground 9 MW CAES is planned to be installed in Queens, New York. The system utilises steel pipes and a modular structure. The duration at rated power is 4.5 hours. The incentives for the installation include frequency regulation and energy shift. The round trip efficiency is about 60-75%.

The next generation of CEAS technology is expected to be Isothermal Compressed Air Energy Storage (ICAES). ICEAS increases the efficiency of the thermodynamic cycle, by compressing and expanding air at near-constant temperature. For further simplicity, the compressor and the expander can be the same machine. Another advantage is that the process does not require natural gas or biogas, see Figure 5.5. The future role of CAES in energy storage is promising, in particular for solutions that manage to combine modularity and cost-effectiveness. The market is expected to grow significantly in near future.

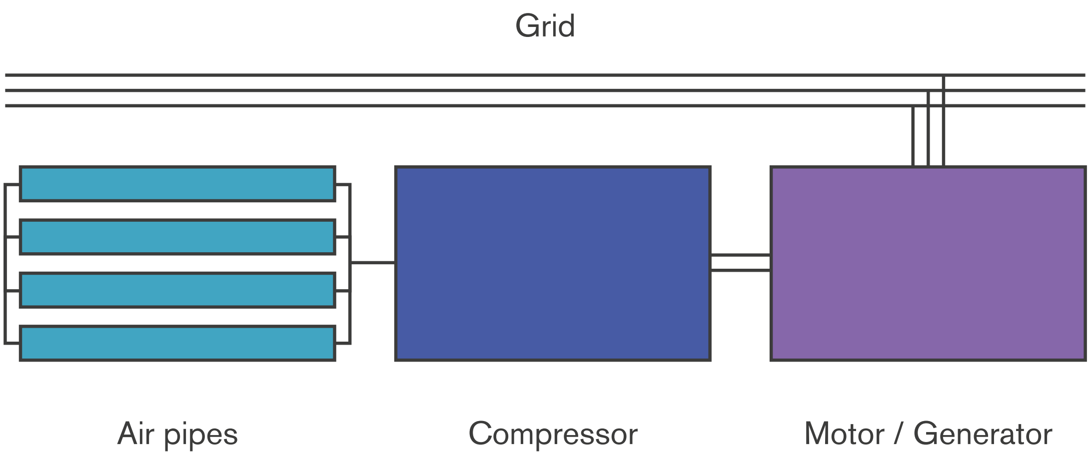

Figure 5.5 Isothermal compressed air energy storage (above-ground)

BATTERIES

Seven battery types are described in this section, most of them technologically mature. The comparison is mainly based on data from a white paper from 2011[5] and Encyclopedia of Electrochemical Power Sources.[6]

Lead acid (PbA) batteries have been commercially available for more than hundred years and offer a mature technology at low cost. PbA battery systems are used in both stationary and mobile applications. They are typically used as starter batteries in vehicles, emergency power supply systems or in stand-alone solar photovoltaic systems. In the period 1910 to 1945, PbA batteries were used for storing electricity in grids. Disadvantages of PbA batteries are, e.g., relatively low energy density,

4 Le, H. and Santoso, S. (2013). Operating compressed-air energy storage as dynamic reactive compensator for stabilizing wind farms under grid fault conditions. IET Renewable Power Generation, 7(6):717-726.

5 IEC (2011). Electrical Energy Storage, White Paper, International Electrotechnical Commission (IEC), Geneva, Switzerland.

6 Garche, J. ed. (2009). Encyclopedia of Electrochemical Power Sources, Elsevier, Amsterdam, The Netherlands.

see Figure 5.2, and the content of lead, a hazardous material often prohibited or restricted. Advantages are the favourable cost, see Figure 5.3, recyclability, and simple charging.

Nickel cadmium (NiCd) batteries have been in commercial use for almost hundred years whereas nickel metal hydride (NiMH) batteries became commercially available about twenty years ago. Compared to PbA batteries, nickel-based batteries have a higher power density, a slightly higher energy density and withstand more charge and discharge cycles. NiCd batteries are, as PbA batteries, capable of performing well even at low temperatures, down to -40°C. However, because of the toxicity of cadmium, these batteries are, since 2006, prohibited for consumer use in Europe. NiMH batteries were developed to replace NiCd batteries and have similar properties as NiCd batteries but higher energy densities. NiMH batteries are considered more robust and safer than Lithium ion batteries but cost about the same.

Lithium ion (Li-ion) batteries are mainly used in mobile applications such as laptops, cell phones, and electric bicycles. Li-ion batteries generally have a high efficiency and are very flexible, where almost any discharge time from seconds to weeks can be obtained. Standard cells can handle more full cycles than many other battery options. Safety is, however, a serious issue and to improve the safety, li-ion battery batteries are equipped with a monitoring unit to avoid over-charging and over-discharging (see Chapter 4 in Systems Perspectives on Electromobility). Due to these special packaging and protection circuits, li-ion batteries are currently costly, see Figure 5.3. The li-ion battery technology is still developing, and there is considerable potential for further progress.

Sodium sulphur (NaS) batteries consist of molten sulphur at the positive electrode and molten sodium at the negative electrode and to keep the electrodes in a liquid form the battery temperature is kept in the range 300-350°C. NaS batteries typically have a discharge time of 6-7 hours and a fast response, in the range of milliseconds, indicating that NaS batteries meet the requirements for grid stabilisation. A major drawback is that a heat source is required to maintain operating temperatures.

The sodium nickel chloride (NaNiCl) battery, also known as the ZEBRA (Zero Emission Battery Research) battery, has been commercially available for the last twenty years. It is a high-temperature battery with an operating temperature slightly lower than the NaS battery (around 270 °C). It uses nickel chloride instead of sulphur at the positive electrode. Compared to NaS batteries, NaNiCl batteries have better safety characteristics, higher cell voltage and can withstand limited over charge and discharge.

A metal air (Me-air) electrochemical cell consists of an anode made from pure metal and a cathode connected to air (oxygen). Among the various Me-air batteries the lithium air battery is the most attractive since its theoretical specific energy is about 100 times higher than most other battery types. However, the mix of lithium and humid air can cause fire, which is a safety risk. Currently only a zinc air battery is technically feasible. A rechargeable Me-air battery system potentially offers low material cost and high specific energy, but no Me-air battery type are commercially available yet.

A flow battery is a type of battery that was originally developed by NASA in the early 70s for space flights. The electrolytes are stored externally in tanks and pumped through an electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the cell whereas the energy depends on the size of the tanks. Flow batteries can be fitted to a wide range of stationary applications including storing energy for durations of hours or days with a power of up to several MW. Flow batteries are classified into redox flow batteries (RFB) and hybrid flow batteries (HFB), combining features of conventional batteries and RFBs. Theoretically an RFB can be recharged within a few minutes by pumping out the discharged electrolyte and replacing it with recharged electrolyte. Both RFBs and HFBs are under development where HFBs have been tested in units up to 1 MW (3 MWh).

A comparison of the level of maturity, energy efficiency, and approximate amount of possible recharging cycles of the different batteries are provided in Table 5.1.

Table 5.1 Comparison main features of different battery types.

Battery type	Commercially available	Round trip efficiency	Approximate cycle life
Lead acid (PbA)	1890	50-92%	500-1500
Nickel cadmium (NiCd)/ Nickel metal hydride (NiMH)	1915/1995	70-90%	2500
Lithium ion(Li-ion)	1990	80-98%.	1000-10 000
Sodium sulphur (NaS)	1990	75%	2500-4500
Sodium nickel chloride (NaNiCl)	1995	89-92%	2500-4500
Metal air (Me-air)	Not yet commercial	n.a.	n.a.
Flow (RFB, HFB)	Not yet commercial	n.a.	n.a.

Today, mainly Lead acid and Lithium ion are used in the small storage systems that exist. The battery types show different characteristics and from the comparison it seems like Sodium sulphur (NaS), Sodium nickel chloride (NaNiCl) and flow batteries could be most promising options for balancing the grid and store electric power. However, since the major concern is the cost of the battery also reuse of traction batteries is often discussed as a viable option for electricity grid storage. The technology choice will then depend on what is used in electric cars.

HYDROGEN STORAGE

A typical hydrogen storage system consists of an electrolyser, a hydrogen storage tank and a fuel cell. An electrolyser is an electrochemical converter that splits water, with the help of electricity, into hydrogen and oxygen. Hydrogen is most often stored under pressure in gas bottles or tanks. To generate electricity, hydrogen and oxygen react in a fuel cell (forming water vapour). It is also possible to use gas motors, gas turbines or combined cycles of gas and steam turbines, instead of a fuel cell, when producing electricity from hydrogen.

Current electrolysers (alkaline) have a conversion efficiency of 60-70%, but high temperature solid oxide electrolysers (SOECs), which are expected to enter the market 2015-2020,[7] are assumed to have an efficiency of more than 70%. Hydrogen has the advantage of being a universal energy carrier, meaning that it can also be sold to other energy sectors, such as transport, heating and to the chemical industry. Challenges for commercial hydrogen storage systems are that the electrolyser must be able to operate intermittently and that the system has to be competitive compared to other electricity storage options. The round trip efficiency is 20-45%.

Various R&D projects carried out over the last 25 years have demonstrated the feasibility of hydrogen storage technology. One example is a hybrid power plant in Germany (Enertrag) which is currently under construction.[8] The plant will produce electricity from wind energy and from biogas in a gas turbine. When the wind power is not directly fed into the grid (when the electricity price is low) it will instead be used to produce hydrogen via electrolysis. When the electricity price is high the stored hydrogen will be converted back into electricity in the gas turbine.

FLYWHEEL

A flywheel energy storage system (FESS) consists of a mechanical rotating wheel, a drive motor, a retaining container, and control devices. The kinetic energy stored in the rotational flywheel is proportional to its inertia and the square of its rotating speed. To charge a FESS, the motor will convert electrical energy to mechanical energy by applying a torque and speed up the flywheel. To discharge the flywheel, the motor will act as a generator and convert the mechanical energy in the system to electrical energy. FESS can be used in power systems for voltage support, provision of system inertia and power quality.[9]

Conventional flywheels are made of high strength steel and have high rotational inertia and rotate at the speed around 3000-5000 rpm (revolutions per minute). The maximum size of the flywheels is limited by tensile strength and homogeneity of the steel.

FESS has the advantages of high power density, high number of discharging cycles, long lifetime, low lifecycle costs and use of conventional materials. The rotating systems are more robust and easy to control. The round efficiency is 80-85%.

In the last decade, a new technology is developed together with the advance of material technology, power electronics, and design techniques. A high-speed

7 Brisse, A. (2013). Key technologies: Solid Oxide Electrolyzer Cell, CO_2 Electrofuels seminar, European institute for energy research (EIFER), Iceland, 12 June.

8 Enertrag (2014). Hybrid power plant.

9 Suvire, G.O. and Mercado, P.E. (2012). Active power control of a flywheel energy storage system for wind energy applications. IET Renewable Power Generation, 6(1): 9-16; Eyer, J. and Corey, G. (2010). Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide - A Study for the DOE Energy Storage Systems Program. Sandia report.

low-inertia flywheel is made of carbon fibre and rotates at much higher speed than conventional flywheels. The motor can be integrated within the flywheel to improve rotor dynamics and make it more compact. To reduce the air friction losses due to high speed, the flywheel is usually encapsulated in a vacuumed chamber. The oil-filmed magnetic bearings are replaced by contactless magnetic bearings. The entire flywheel and the rotor of the motor are magnetically levitated in the vacuum. The power flow in or from the flywheel is controlled by power electronics.

A high-speed flywheel just weighting a few kilograms can reach a power of about 200 kW at 50 000 rpm. An array of hundreds of flywheel units can form a 20-50 MW energy storage station. Even though the carbon fibre composite flywheels have high mechanical strength and low weight, the steel flywheels are still preferred as low-cost and reliable alternatives.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Magnetic energy is often used as an intermediate energy form in a lot of energy conversion apparatuses, such as generators, transformers and motors.

In order to increase the energy density to a competitive level, the magnetic field intensity needs to increase. This is accomplished in Superconducting Magnetic Energy Storage (SMES) that is comprised of a superconducting coil, a power electronic converter, and a cooling system.

SMES is divided in low temperature superconducting (LTSC) and high temperature superconducting (HTSC) devices. The former is related to the conventional superconductors that become superconducting below a temperature of 20 K, or -253 °C. High temperature superconducting (HTSC) was discovered in 1986. The highest temperature for which superconducting has been recorded is 138 K, or -135 °C, reported in 2009. To maintain such extreme temperatures a cryogenically cooled refrigerator is needed. Even though the operating losses of the cooling system do not significantly influence system efficiency, the extra equipment makes the system more complicated and expensive.

One advantage of SMES is its very short response time (<100 ms). SMES is therefore suitable for improving grid stability of distribution and power quality in local networks. Another advantage of SMES is its high round trip efficiency (up to 95%). Finally, the main components are stationary, without moving parts, which contributes to high operational reliability.

SMES is still costly compared to other energy storage systems. The superconducting ceramics used in the coils is still a key issue for SMES due to high temperatures they have to resist. Recent developments focus on the costs of manufacturing the wires and increasing the current density and mechanical strength. The supporting mechanical structure is another challenge for large-scale SMES. Integration into power units may increase the competitiveness.[10]

10 Nielsen, K.E. (2010). Superconducting magnetic energy storage in power systems with renewable energy sources. Master Thesis, Norwegian University of Science and Technology.

SUPER CAPACITORS

Supercapacitors (SC) are electrochemical capacitors and are also called ultracapacitors or electric double-layer capacitors. Supercapacitors can be considered as a mix between conventional capacitors and batteries. They have much higher energy density than conventional capacitors, but much lower than any battery. Because of their high speed of charging and discharging, supercapacitors have 10-100 times higher power density than conventional batteries and the round trip efficiency is about 70-80%.

Supercapacitors have already found wide applications in consumer and industrial products like laptop computers, GPS, and other mobile devices and tools. With the advantages of fast charging and long cycle life, supercapacitors are used as alternatives to batteries in cable cars, wind turbines pitch systems, and motor starts for diesel vehicles. For energy recovery in trains, trams, busses, and electric or hybrid vehicles, supercapacitors are used in combination with batteries to increase energy efficiency and prolong the battery lifetime.

Supercapacitors are one of the most promising technologies for short-term energy storage. Research on new materials is intensive and includes exploration of nanotube electrodes, graphene electrodes, and lithium-ion supercapacitors.

OTHER WAYS OF STORAGE

There are many different ways to store energy. So far, we have discussed technologies where electricity is converted, stored and converted back to electricity again, but there are also other options.

Hydropower dams are the most common way to store energy (potential energy) that later are to be used for electricity production. The system can be made in large scale and with a high efficiency but the environmental effects might be considerable (see Chapter 6). Due to its advantages, hydropower with large dams is often used to control the grid wherever it is possible (Chapter 11).

There are also other ways where energy can be stored for later conversion into electricity. One example is thermal energy storage in concentrated solar thermal power plants (CSP) where excess solar energy can be stored in molten salts (Chapter 4). The advantage is the capacity to store large amounts of energy in a small volume and with a minimal temperature change, which allows efficient heat transfer. In Seville, Spain, the thermal storage system extends the daily electricity generation to over 12 hours in winter and up to 20 hours in summer. Disadvantages are the risk of liquid salt freezing at low temperatures and the risk of salt decomposition at higher temperatures. For liquid systems different concepts with a combination of nitrate salts and oil are under discussion. The round trip efficiency can exceed 70%.

By introduction of some reserve production and storage of produced goods may almost all manufacturing be used as electricity storage, often called demand side management (Chapter 10).

One example of a process with a kind of inbuilt storage capacity is to convert the excess electricity via hydrogen to carbon based fuels such as synthetic natural gas (SNG) or methanol, so called electrofuels. These fuels can be stored and later be used in the transportation sector or as feedstock in the chemical industry and can utilise existing infrastructure (Chapter 12).

CONCLUDING REMARKS

The grid needs to adapt to the new situation with a large amount of renewables in the near future. The need for grid extension can be limited by introduction of electricity storage. Storage technology can have multiple uses in the electric grid system which complicates any comparison between different storage technologies. Electricity storage technologies not only have to compete with each other but also with other means to solve grid balancing issues. Examples are systems where energy can be stored before it is converted into electricity and systems where electricity is converted to some storable goods that can be used when needed and, finally, systems that apply curtailment of production.

Today there are very few incentives to install storage or sell storage-like services; however, with larger power fluctuation on the grid and price fluctuations on the power market that can be expected with a large scale introduction of renewables, the demand for new solutions will grow.

6

ASSESSING ENVIRONMENTAL IMPACTS OF RENEWABLE POWER

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INTRODUCTION

Electrical power systems based on renewable energy sources are often intuitively perceived as environmentally benign. This may be true at least for comparisons between electricity generated by combustion of fossil fuels and non-combustion-based renewable sources, at least in terms of contributions to greenhouse gas (GHG) emissions (Chapter 7) and other air polluting gases. However, there exists no system generating electric power for applications on commercially relevant scales that is completely without unwanted environmental side effects; it is more a question of which environmental effects and their severity. Given the serious implications of climate change, the motivation to find substitutes for fossil-based energy systems is strong, but it is likewise important to not solve one environmental problem by creating another, although of a different type. In order to prevent that, systematic investigations and assessments of the environmental performance of different renewable electricity sources become crucially important.

The methods applied for environmental assessments of renewable energy sources need to be applicable to a number of fundamentally different energy systems, spanning from the construction of offshore wind power farms to hydroelectric power dams. These different energy sources provide a set of very different environmental impacts occurring in many different ecosystems. The challenge of the environmental assessment methods is to deliver assessment results that are fair and encompass the various significant environmental impacts under different conditions. Particularly when seen from a life-cycle perspective, encompassing the raw material extraction, production and use of the energy, a number of environmental impacts in terms of both resource extraction and emissions become apparent, even for renewable energy systems. Therefore, careful consideration of environmental impacts of renewable energy systems along the entire life-cycle of the energy systems is important to avoid serious environmental repercussions (see also Chapter 8).

In addition, based on earlier experiences, it is apparent that the specific design, location and scale of e.g. hydro and wind power installations are factors that to a large extent determine their environmental impacts (see also Chapter 9). A smaller installation will often result in less environmental impact than a large-scale. These factors are so-called site-dependent and cannot easily be assessed in a standardised manner, which calls for flexible and adjustable assessment methods that can be adapted to the specific case. An unfortunate location of a hydropower dam does not mean that the entire technology carry unacceptable environmental impacts, just that the specific location or design in the specific case is unfortunate.

This chapter aims at a general description of the challenges posed when trying to assess environmental impacts of renewable energy technologies and to, with limited technical detail, introduce the ways environmental impacts are assessed. Furthermore, a few specific examples will be employed to exemplify environmental impacts of renewable power systems.

HOW TO ASSESS ENVIRONMENTAL IMPACTS?

The most important aspect of the environmental assessment methods is to allow for comparisons. The driver of comparisons of alternatives regarding renewables is to provide arguments underpinning the choice of (1) energy technologies, (2) their design of specific installations, and even (3) the long-term development of large energy systems. The challenge is to cover the many different renewable energy sources, their construction, operation and decommissioning phases, and the different kinds of environmental impacts associated.

In general, environmental assessment is a matter of linking the human activities related to the (renewable) energy source under consideration with the environmental impacts of concern. This idea is illustrated in Table 6.1.

The framework in Table 6.1 illustrates the linking of human activities during the life-cycle stages of the energy infrastructure to identified environmental endpoints of concern. Stressors are factors, external to an organism, which will restrict its availability of resources, growth or reproduction. The outcomes of exposure to stressors are changed ecosystem structure or functions. In order to indicate these, environmental indicators can be applied.

Environmental indicators can directly indicate effects on endpoints, or along the pathway of stressors from source to endpoint. Pressure-state-impact (PSI) type of indicators was described in OECD-reports[1] and further developed into the

1 See e.g. OECD (1993). Core Set of Indicators for Environmental Performance Reviews, A Synthesis Report by the Group on the State of the Environment. Paris, France.

European driving forces-pressures-states-impact-response (DPSIR) framework.[2] Several hundreds of indicators related to environmental pressures, states and impacts have been identified and likewise the number of ecologically relevant endpoints is very large.

Table 6.1 Framework that combine life-cycle thinking and an ecological risk assessment approach with examples of stressors, endpoints and environmental indicators. PSI stands for pressure-state-impact.

Life-cycle stage of renewable power technology	Stressors	Environmental indicators along pathways or for effects on environmental endpoints (PSI-indicators)	Endpoints
Production of raw materials & manufacturing of power generating infrastructure	Resource extraction, emissions from mining, emissions from power production for manufacturing	Emitted amount of specific substance like copper emitted from mining (ton/year)	Atmospheric energy balance, nutrient status of sea water
Installation	Habitat destruction or disturbance	Area occupied by installations (ha)	Specific species, or biodiversity in general
Operation and maintenance	Emissions from operations	Emitted amount of specific substance, like greenhouse gas emissions (ton/year), collisions caused by moving turbines (no. of individuals of specific specie)	Atmospheric energy balance, nutrient status of sea water, specific species, or biodiversity in general
Decommissioning & waste handling	Toxic emissions from waste handling	Emitted amount of specific toxic substance, like leakage of lead from landfills (ton/year)	Specific species, or biodiversity in general

In addition to the description and comparison of environmental impacts, trade-offs between technologies, designs, costs and, accordingly, between different environmental impacts are of great importance. So beside direct comparisons within the same category of impacts, there is a wish to perform trade-offs between environmental impacts. Trade-offs are unavoidable when decisions are taken, and when dealing with collective decisions, trade-offs should involve a conscious weighing of perceived positive ("gains") and negative ("losses") consequences of different energy systems. This ideal is, however, seldom pursued in real world situations.

The idea of linking causes to effects, illustrated in Figure 6.1, is at the core of the different environmental assessment methods. These include retrospective, prospective and product-related, process-related and project-related methods, as identified by Ness and colleagues.[3] Despite their differences, both the process-

2 Smeets, E. and Weterings, R. (1999). Environmental indicators: Typology and review. Copenhagen, European Environment Agency.

3 Ness, B. et al. (2007). Categorising tools for sustainability assessment. *Ecological Economics,* 60:498-508.

and project-related types of environmental assessment (e.g. Environmental Impact Assessment, EIA, Strategic Environmental Assessment, SEA, and Ecological Risk Assessment, ERA) and the product-related, non-site specific, type of assessment methods (e.g life-cycle assessment, LCA) maintain the same basic idea. The differences between assessment methods lie more in how the various methods are designed and organised with regards to stressors, indicators and endpoints.

Life-cycle assessment (LCA) has from its inception as a product design support method developed to an excellent mean for quantitative comparisons of the environmental performance of products.[4] The way LCA is standardised for application on products with long and complex product chains has made it a popular method of choice.[5] However, the standardisation of impacts assessment within LCA makes site-independent and more specific spatial considerations difficult, if not impossible, to include. Within LCA, the comparability issue has been high on the agenda from the very beginning. Making trade-offs within LCA is also possible in the voluntary normalisation and weighting steps. These methods are, however, much dependent on subjective values.

Inclusion of spatial differences are on the other side the strength of EIA, which is also flexible regarding contents and open for information from various other environmental assessment methods. Many EIAs have, on the other hand, been less clear when it comes to structured and systematic comparisons of alternatives. This shortcoming has been improved in the development of EIA into the SEA procedure, in which the formulation of alternatives to assess together with the establishment of base-line conditions, environmental indicators and recurring monitoring are important tenets.[6] Furthermore, trade-offs has not been focused enough in EIA, since much practice in the field has been done in order just to fulfil legal requirements.[7]

The procedures and rules for trading-off is a key issue that has got specific attention in sustainability assessments since the various social and ecological aspects of sustainability require radically different approaches for trade-off than earlier recognised.[8] Furthermore, trade-offs are needed to be performed *under* the core criteria for sustainability assessment, which among other aspects include maintenance and enhancement of socio-ecological system integrity; resource maintenance and efficiency; and precaution and adaptation. These rules and criteria await their application in assessments of renewable energy sources, and does clearly go beyond only environmental considerations.

The recent developments within sustainability assessments may be of specific interest for environmental assessments of renewable energy technologies. This

4 See e.g. Baumann, H. and Tillman, A.-M. (2004). The Hitch Hiker's Guide to LCA - An orientation in life cycle assessment methodology and application, Lund, Sweden, Studentlitteratur.

5 ISO (2006). Environmental management – Life cycle assessment – Principles and framework. Geneva, International Organisation for Standardisation.

6 Therivél, R. (2004). Strategic Environmental Assessment in Action, UK, EarthScan.

7 Runhaar, H. et el. (2013). Environmental assessment in The Netherlands: Effectively governing environmental protection? A discourse analysis. *Environmental Impact Assessment Review,* 39, 13-25.

8 Gibson, R. B. (2006). Sustainability assessment: basic components of a practical approach. *Impact Assessment and Project Appraisal,* 24, 170-182; Morrison-Saunders, A. & Pope, J. (2013). Conceptualising and managing trade-offs in sustainability assessment. *Environmental Impact Assessment Review,* 38, 54-63.

since the problem of comparing renewable energy technologies from an environmental point of view brings about a number of complicated, or even wicked, problems to handle.[9] The wickedness is due to the fact there will be no simple formal set of criteria for evaluating the environmental performance. Despite the recommendations of Gibson[8] and Morrison-Saunders and Pope[8], further specifications may be required, and as often shown - the devil is in the details. Low emission of GHGs per kWh of wind power will not easily converse antagonists claiming that wind power is ugly, breaking the horizon line of their sea views, or bird watchers worrying for birds colliding with the turbines. The trouble is in the incommensurable units of GHG emission on the one hand and the preferences related to the appreciation of an unbroken horizon, or birds, on the other. The complication becomes especially obvious as the groups and individuals involved often do not communicate making the bridging of these types of controversies difficult. If the trade-off rules of Gibson[7] can overcome this kind of troubles remain to be demonstrated in further studies.

Under the wide umbrellas of assessment procedures such as EIA, SEA and sustainability assessment, a number of more specific assessment methods can be used. Ness and colleagues identified in their review of methods for sustainability assessment at least 30 families of methods, of which about half are fully or partly applicable for environmental assessments of renewable energy systems including comparing and trading-off.[10]

WHAT ENVIRONMENTAL IMPACTS TO ASSESS?

The questions of which environmental assessment method to apply and how to perform trade-offs need to be handled in parallel with considerations of what environmental impacts to assess. As pointed out, there are different kinds of impacts and the renewable energy sources differ in terms of which environmental impacts they cause. Therefore, performing an environmental assessment of renewable energy sources is a matter of reducing the complexity and to establish boundaries for the assessment based on the initial considerations of comparability and trade-off.

Given the many and complex interactions in ecosystems, simplification of environmental impact is a challenging task. Ecological Risk Assessment, ERA, has developed into a useful method also for the assessment of renewable energy sources.[11] The ERA framework has the ability to inform tailor-made, detailed and site-specific assessments. The basic idea is to make quantitative assessments of the impacts of stressors on selected endpoints. Therefore, one of the most crucial aspects is the selection of endpoints for the ERA.

What are the ecological effects to focus? A large number of interlinked physico-chemical and biological parameters can be identified in an ecosystem and pointing out particular species such as the peregrine falcon, or a physico-chemical

9 Rittel, H. W. J. & Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences,* 4, 155-169.
10 Ness, B. et al. (2007). Categorising tools for sustainability assessment. *Ecological Economics,* 60:498-508.
11 Efroymson, R. A. (2009). Wind Energy: The Next Frontier for Ecological Risk Assessment. *Human and Ecological Risk Assessment,* 15, 419-422; Hammar, L., Wikström, A. & Molander, S. (2014). Assessing ecological risks of offshore wind power on Kattegat cod. *Renewable Energy,* 66, 414-424.

parameter like water turbidity, to be the focal point of an assessment cannot be done in one way only. Individuals, including environmental scientists, have different preferences regarding object of protection and the "best" way to reduce the complexity of the ecosystem down to some few selected parameters in focus. There are many, potentially crucial, abiotic and biotic parameters in an ecosystem that can be observed. Wind power may cause fatalities to birds due to collisions if inappropriately located, some turbines can leak oil from bearings under unfortunate conditions, and noise can disturb. Hydropower may rely on dams hindering migrating fish, and dams can generate methane from inundated rotting biomass.

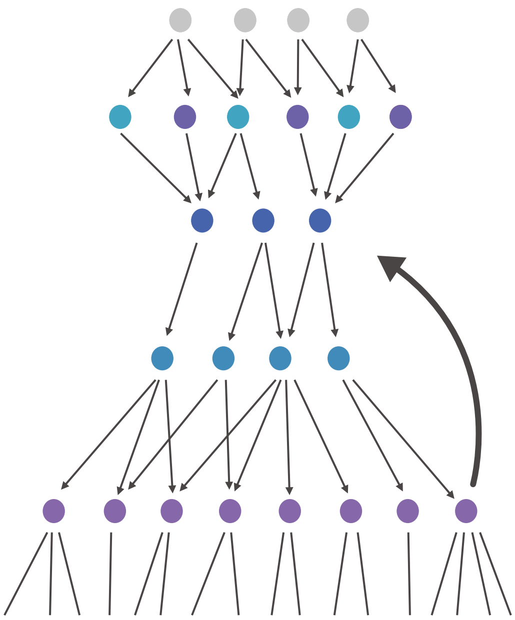

Figure 6.1 The ecological cause-effect cascade that follows the introduction of a stressor in an ecosystem is a consequence of the linkages mainly in the food-web. Due to links and feedback loops within the ecosystem, impacts will not be limited to the first order, or direct, effects observable close to the stressor source. However, biotic and abiotic negative feedback regulation within the system will often dampen effects to stay within a given range until a sudden shift may force the system into another relatively stable range under a new set of negative feedbacks. Nyström, M. et al. (2012).

The identification of endpoints, or objects of protection, is therefore a specific challenge of ERA and other environmental assessment methods. Different approaches such as checklists, expert judgment and participatory approaches for identification of endpoints have been suggested in order to address this challenge.[12] In LCA, the endpoints, called areas of protection, are pre-defined to be human health, the natural environment (with a number of more or less specified end-points) and natural resources.[13]

It is also possible to use political goals for the identification of endpoints. In a Swedish study, the Swedish National Environmental Objectives (SNEOs) were used in a stepwise procedure to identify more specific endpoints, and indicators,

12 US EPA (1998). Guidelines for Ecological Risk Assessment; Burgman, M. A. (2005). *Risks and Decicions for Conservation and Environmental Management,* Cambridge, Cambridge University Press.
13 Baumann, H. and Tillman, A.-M. (2004). *The Hitch Hiker's Guide to LCA - An orientation in life cycle assessment methodology and application,* Lund, Studentlitteratur.

connected to the more vaguely formulated SNEOs.[14] The procedure therefore relied on a deconstruction and specification of the SNEOs down to endpoints, and related environmental indicators, representing the SNEOs and linking these indicators to stressors from various life-cycle stages of renewable energy sources (see example in Figure 6.2).

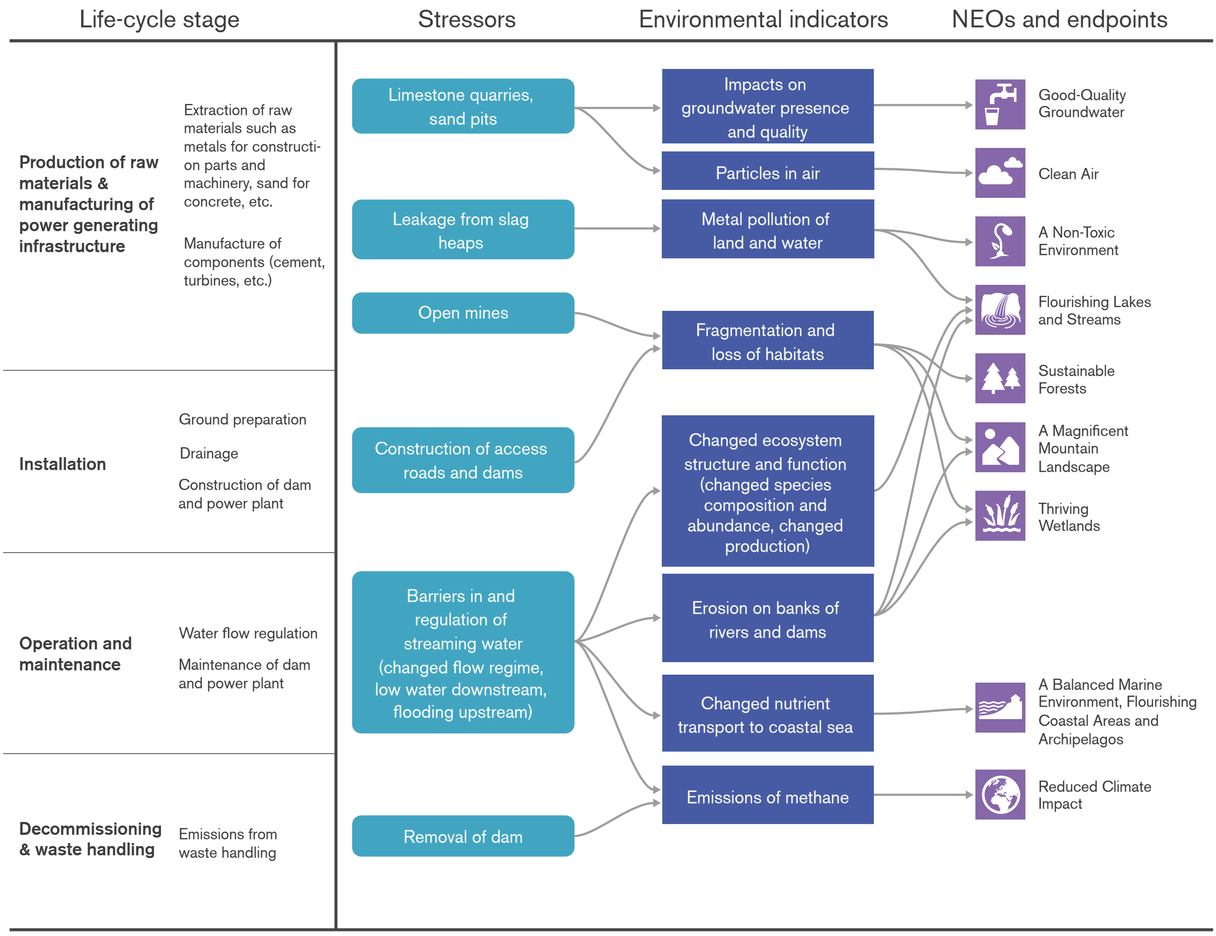

Figure 6.2 The direct links between Swedish National Environmental Goals (SNEOs) and stressors emerging from hydropower production systems. Indirect links of the prominent background systems that contain e.g. energy production's and transports' contribution to the total environmental impact were not included in the assessment. The direction of arrows indicates the material influences in the cause-effect chain from release or occurrence of stressors to effects on endpoints. The procedure for establishing links works in the opposite direction starting with the SNEOs and their specification into indicators and linking to human activities along the life-cycle stages of the energy system.

THE CASE OF HYDROPOWER

Hydropower provided globally 3700 TWh in 2012, which was approximately 2% of the total primary energy supply.[15] In the last decade, output has grown by 100 TWh/year annually, and the potential provision is estimated at 8 000-16 000 TWh/yr (Chapter 3-4).

In Sweden, 67 TWh, (or 43%, annual means) of the electrical energy generated stems from hydropower.[16] The main operator Vattenfall AB, contribute 32 TWh

14 Molander, S., et al. (2010). Förnybara energikällors inverkan på de svenska miljömålen. *Naturvårdsverket, Rapport 6391.* Stockholm, Sweden.
15 IEA Energy statistics (2013).
16 Swedish Energy Agency Energy Statistics (2014).

(48%) and has performed environmental assessments for their operations of hydropower in accordance with the Environmental Performance Declarations (EPD).[17] These assessments of hydropower cover 13 Swedish installations or about 15% of all Swedish hydropower, representatively spread across the country. The report includes stringently performed LCAs according to documents of the International EPD Consortium (IEC).[18] The assessments have also included environmental information based on other methods for impacts on biodiversity, land-use and environmental risks in accordance with the Product Category Rules (PCR) of IEC.

The LCA reported by Vattenfall covered installation (including the release of GHG due to inundation of land in reservoirs), operation and maintenance, and distribution.[16] The LCA inventory is extensive and includes 25 used resources, 10 types of energy inputs, 25 emitted substances with impacts on global warming, ozone-depletion, acidification, eutrophication or ground level ozone, and 17 emitted toxic, radioactive or otherwise environmentally significant substances (e.g. ammonia, arsenic, oil and polyaromatic hydrocarbons). The depletion of phosphorus due to deposition in sediments of water reservoirs is furthermore included, together with 11 waste streams.

The methods employed for the additional environmental information regards impacts on land-use change, specifically on biodiversity, and environmental risks in a broad sense. The estimation of impacts on biodiversity applies a method specifically developed by Vattenfall. The so called Biotope Method is based on a categorisation of land into four different biotope categories and land-use change caused by the construction of hydropower plants and the huge reservoirs.[19] The Biotope Method is regarded as admittedly coarse by Vattenfall and does not cover fragmentation and barrier effects or effects due to the changed flow regime.[16] These effects are known to contribute significantly to the environmental impacts, but also differ much due to the specific design, size and location of the installations.[20]

A further comparison of the endpoints covered by the EPD-report's combination of LCA and other methods and data underlying Figure 6.2 shows mostly overlapping categories where the Vattenfall EPD reports many, and detailed, environmental flows for the LCA-case, which is far beyond the coverage of the SNEOs and their related indicators. The EPD report covers many environmental aspects and the coverage is much better than ordinary EIAs or LCAs due to the combination of assessment methods.

This is clearly a benefit, but still many significant effects are not covered, such as the impacts on biodiversity along the rivers due to the altered flooding regime or the altered nutrient transport to the Baltic Sea. Furthermore many of the installations included were constructed in the period prior to modern legislation. EIAs

17 Vattenfall (2011). Certified Environmental Product Declaration EPD of Electricity from Vattenfall's Nordic Hydropower. *EPD.* Stockholm: Vattenfall AB.

18 See references in Vattenfall (2011).

19 Kyläkorpi, L. et al. (2005). The Biotope Method 2005 - A method to assess the impact of land use on biodiversity. Vattenfall AB.

20 WCD (2000). Dams and Development - a new framework for decision-making. London and Sterling, VA: World Commision on Dams.

were never performed,[21] making stringent comparisons to real baseline conditions impossible, and without that only comparisons to other, non-exploited, sites of similar ecosystems can be performed leaving room for some uncertainty. However, major impacts, such as impacts on fish migration, can be indirectly inferred.

A notable difference between the different installations concerns the land-use change caused by the inundation upstream dams. Expressed as loss of critical biotope per energy gained the results spans a range of around 100 between the least and the most biotope damaging among the studied Swedish hydropower plants (from around -15 ha/GWh electricity to -1500 ha/GWh). This is in accordance with the wide span of the ratio of reservoir area to annual mean power production, which is from 0.2 to 47 ha/GWh. A similar wide span, but on a global scale, has been reported for GHG emissions from hydro power reservoirs and a geometric mean emission of methane among some 150 reservoirs of 0.6 gCH_4/kWh, with a geometric standard deviation equal to 46 was found. This corresponds to a span from about 10 µg to 1 kg CH_4/kWh. Hertwich points out that it is likely that for maybe up to 10% of hydropower installations the biogenic GHG contribution reach levels comparable with electricity generation from natural gas combined cycle power plants, which are among the low-GHG-emitting fossil fuel systems.[22]

It is clear that the local conditions and the specific design of hydropower installations strongly influence the environmental performance, both regarding impact on biodiversity and GHG.

THE CASE OF WIND POWER

Wind power is globally increasing at a fast rate and the installed capacity was 280 GW in 2012, with a total production estimated at around 500 TWh in the same year. The global potential might be of the same order of magnitude as current global primary energy supply (Chapter 3).

In Sweden, wind power supplied 7 TWh in 2012, up from 1 TWh in 2006. The production in 2012 corresponds to 4% of total power supply.[23] Wind power is rapidly expanding despite an extensive debate on various impacts - environmental, social and technical (see also Chapter 9, 11 and 13-15).

Vattenfall AB is also involved in Swedish wind power and owns, and operates, 11 wind farms, 8 onshore and 3 offshore, with 129 turbines. In 2011, the installed capacity was 0.2 GW and the electricity production reached 0.7 TWh. Also for wind power Vattenfall has performed an environmental assessment in accordance with the Environmental Performance Declarations (EPD).[24] The assessment cover four Swedish installations or about 80% of Vattenfall's Swedish wind power (or 9% of all Swedish wind power), representatively spread across the country. As

21 Nizami, A. S. et al. (2011). Comparative analysis using EIA for developed and developing countries: Case studies of hydroelectric power plants in Pakistan, Norway and Sweden. *International Journal of Sustainable Development and World Ecology,* 18:134-142, and references therein.

22 Hertwich, E. G. (2013). Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA. *Environmental Science & Technology,* 47:9604-9611.

23 Swedish Energy Agency Energy Statistics (2014).

24 Vattenfall (2013). Certified Environmental Product Declaration EPD of Electricity from Vattenfall's Nordic Wind Farms. *EPD.* Stockholm: Vattenfall AB.

for the hydropower assessment the environmental assessment of wind power followed the EPD-guidelines and included impacts on biodiversity, land-use and environmental risks.

As for the hydropower LCA, the wind power LCA inventory is extensive and includes 26 used resources, 10 types of energy inputs, 25 emitted substances impacting on global warming, ozone-depletion, acidification, eutrophication or ground level ozone, and 17 emitted toxic, radioactive or otherwise environmentally significant substances (e.g. ammonia, arsenic, oil and polyaromatic hydrocarbons), together with 11 waste streams.

As in the case of hydropower, a set of complementary methods provides valuable insights on land-use, biodiversity, environmental risks (mostly leakage of oils and fluids related to accidents with transports during maintenance), electromagnetic fields, noise and visual impacts. The assessed wind power plants were constructed in the time period from 1998 to 2010, during which base line conditions have been examined giving, in contrast to hydropower, the possibility to monitor changes caused by the installations. This has been of particular interest regarding impacts caused by the offshore wind farms on the marine benthic ecosystems where effects are clear, but often considered positive since biodiversity increase due to the introduction of hard substrata in soft-bottom dominated areas and due to shelter from fishery (see also Chapter 8).[25]

Collisions between turbines and birds and bats have attracted considerable interest, but the Vattenfall report, in agreement with most studies, consider collision risk to be low and only important in exceptional cases of badly located wind farms.[26]

Another risk, that has attracted much less interest, is related to spills of lubricants from the operation (including accidents) of wind turbines. The risk is mentioned in the Vattenfall report and a report has found that such risks need further observations in order to be estimated and uncertainties reduced.[27]

As for hydropower a notable difference between the different installations concerns the land-use change caused by the installations. Expressed as loss of biotope per energy gained the results indicate a difference of about 200 times between the less area efficient on-shore and the off-shore wind farms (Table 6.2). However, a comparison between the on-shore wind power case and the large scale hydropower of the huge installations in the Lule River indicates that generation of electricity is about half as area efficient as land-based wind power, but very much less area efficient in comparison to the off-shore wind power case of Lillgrund.

25 Molander, S., et al. (2010). Förnybara energikällors inverkan på de svenska miljömålen. *Naturvårdsverket, Rapport 6391.* Stockholm, Sweden; Wilhelmsson, D. and Malm, T. (2008). Fouling assemblages on offshore wind power plants and adjacent substrata. *Estuarine Coastal and Shelf Science,* 79:459-466; Reubens et al. (2014). The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. *Hydrobiologia,* 727:121-136.

26 Eichhorn et al. (2012). Model-Based Estimation of Collision Risks of Predatory Birds with Wind Turbines. *Ecology and Society,* 17; Bright et al. (2008). Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. *Biological Conservation,* 141:2342-2356.

27 Arvidsson, R. and Molander, S. (2012). Screening Environmental Risk Assessment of Grease and Oil Emissions from Off-Shore Wind Power Plants. Environmental Systems Analysis, Chalmers University of Technology, Göteborg.

Table 6.2 Examples of land appropriation for renewable power production comparing on-shore and off-shore wind power and large scale hydropower using an indicator for land-use change related to net electricity production. Source: Adapted from Swedish Energy Agency Energy Statistics (2014) and Vattenfall (2013), along with specific data for the Lule River power plants from Vattenfall (2014).

	Mean annual net production (GWh)	Annual mean net electricity production per appropriated area (GWh/ha)	Biotope categories	Area before installations (ha)	Area after installations (ha)	Change of biotope category (ha)	Change of biotope per annually generated electricity (ha/GWh)
Wind farm - on-shore	**240**	**4.3**	Critical biotope	5.4	0	-5.4	-1.2
Stor-Rotliden			Rare biotope	21	0	-20.7	-4.8
(Northern Norrland)			General biotope	39	10	-29.4	-6.8
			Technotope	5.7	61	55.5	12.8
Wind farm - off-shore	**320**	**1400**	Critical biotope	1.8	1.8	-0.03	$-1.9 \cdot 10^{-05}$
Lillgrund			Rare biotope	2.3	2.3	-0.06	$-3.9 \cdot 10^{-05}$
(Öresund)			General biotope	2.9	2.8	-0.15	$-1.1 \cdot 10^{-04}$
			Technotope	0.18	0.41	0.23	$1.6 \cdot 10^{-04}$
Hydro power	**13800**	**2.0**	Critical biotope	5870	0	-5870	-2920
Lule River			Rare biotope	863	35	-829	-413
(Northern Norrland)			General biotope	3650	3500	-157	-78
			Technotope	110	6960	6850	3410

CONCLUDING DISCUSSION

In some aspects, impacts from renewables are very different from the ones caused by the fossil fuel based systems. Particularly land-use, and subsequent environmental impacts, is an example of such impacts. Other impacts, such as air pollution from biomass combustion (while not included in this book), resemble to large extent air pollution from fossil fuel combustion. Such combinations of differences and similarities provide difficulties when comparing and relates to the question of what in fact is compared.

Comparisons may be on the level of technologies or relate to specific designs (see also Chapter 7-8). The comparisons can also deal with specific installations. For this last category, site-specific conditions will determine the direct environmental consequences to a large extent. To reach further, the combination of LCA and other environmental assessment methods seem to be a way forward that has been applied to a certain extent in the EPD approach. Wide differences in environmental impact are demonstrated within the technologies of hydro and wind power, as are described above. These differences need to be considered along with average differences between technologies. The scale of the installations is also of importance since the relationship to environmental impact is not always linear. The extensive coverage of flows in LCA studies makes detailed comparisons across technologies possible. However, the normalisation of the flows to a certain base for comparison - one functional unit - will disregard differences in scale and site-specific factors.

It may be fair to state that simple between-technologies-comparisons can only be done for some specific parameters, see e.g. Table 6.2. It is also possible to compare LCA-based estimates of contributions to global warming from GHG emissions (Chapter 7). However, even that turns out to be a less straightforward exercise, e.g. regarding the biogenic carbon dioxide emissions of large hydro-power installations.

There are also severe difficulties related to incommensurable effects. It is not easy to compare widely different types of impact. It is even difficult to compare different impacts on biodiversity between e.g. wind power, where collisions of birds and bats occur, and hydropower where fish are injured or killed when passing turbines, dams are hindering fish migration and flooding regimes are disturbed. Experiences point to a practice where novel suggestions regarding trade-offs need to be considered.

Notwithstanding the mentioned difficulties, environmental assessments can and need to be performed. To define the questions regarding what to assess, and how to do it, broader and more consistent approaches can be a way forward.

Finally, there are no energy systems without some environmental repercussions. A transition to renewable power will not eradicate the benefits of reducing energy demand, and strategies aiming at efficient use of energy will remain crucial to limit the environmental impact of power production.

7

ENERGY BALANCE AND CLIMATE IMPACT OF RENEWABLE POWER: IS THERE CAUSE FOR CONCERN?

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INTRODUCTION

It is generally acknowledged that the conversion of renewable energy flows into electricity in itself has no or negligible climate impact.[1] However, the conversion will always require production, maintenance and end-of-life treatment of power plants. These processes may very well involve emissions of greenhouse gases. It has thus been pointed out that the whole life-cycle of the power plant needs to be taken into account in assessments of the climate impact of renewable power production.

Most of the life-cycle emissions stem from the use of fossil fuels in different production steps. Hence, the climate impact of renewable power is tightly linked

1 Bioenergy is an energy stock, or fund, and not a flow in the perspective taken in this book, and is therefore not considerd. If renewable electricity were to be converted and stored in the form of electrofuels (Chapter 12), greenhouse gases could leak or be formed in a later combustion step. Massive deployment of wind, solar and ocean thermal energy conversion (OTEC) may to a limited extent impact local climate (see also Chapter 3 for discussions on global limits to wind and OTEC deployment and some references on the topic).

to energy requirements and more specifically to the balance between energy input and energy output.

The discussion on energy balances, in fact, predates the concern for climate impact by a couple of decades and deserves some attention in its own right. The debate goes back at least to the beginning of the 1970s when it was observed that the energy payback time of some solar cell (PV) modules could be as high as 40 years and that the net energy output was zero or even negative. The concern for low energy return on energy investment has gained renewed interest in recent years, now with the low net energy output of some biofuels in focus.

One primary rationale for the concern with low energy return on energy investment relates to the viability of individual technologies. A technology with a small or negative net yield can be useful in specific niches where the technology is able to supply small quantities of electricity for specific purposes, such as solar cells powering satellites or providing light in rural villages in developing countries. However, if the technology is going to contribute significantly to world energy supply, a relatively high energy return is needed. This concern has also been taken beyond the level of individual technologies, to the set of all available energy technologies. It has been argued that the decreasing energy return on energy investment in oil extraction and refining due to exhaustion of easily accessible resources of high quality, together with the, by some evaluations, low energy return on investment from renewables, could have macroeconomic consequences and slow down economic growth in the coming decades.[2]

Measures of energy balance may also be used as a performance indicator to benchmark technologies, to argue for one or the other. This rests on an assumption that energy efficiency is important, either due to limited availability of energy resources or some specific energy carriers, or due to the fact that all energy conversion carries environmental and social costs. One benefit of using energy indicators in technology assessments, compared to indicators of more specific resource scarcities or environmental effects, is that they capture an intrinsic property of the technology itself rather than the properties of the particular background energy system which may change between regions and over time.

The question in focus in this chapter is if there is cause for concern related to the energy requirements and greenhouse gas emissions in the life cycles of renewable power technologies. To answer this question we will first introduce some measures of energy balance and climate impact and point out some important methodological considerations and then provide some empirical evidence. The scope is restricted to the power plants (Chapter 4), while electric grids and energy storage systems are not included (Chapter 5). One needs to observe that the climate impact and energy requirements are only two aspects out of many environmental issues that require the attention of decision makers, albeit two important ones (see e.g. Chapter 3 on resource availability and Chapter 6 and 8 on other environmental effects).

2 Hall, C., et al. (2009). What is the Minimum EROI that a Sustainable Society Must Have? *Energies* 2(1): 25-47.

MEASURES OF LIFE-CYCLE ENERGY BALANCE AND CLIMATE IMPACT

The simplest measure of energy balance is the *energy payback time* (EPBT). It is particularly useful in assessments of technologies that is characterised by a large initial energy investment, which can, so to speak, be paid back over time as the device generates electricity. At the EPBT the cumulative output balances the initial input. To generate a significant amount of net output the EPBT needs to be significantly shorter than the lifetime of the device. To be complete the energy investment also needs to include energy required for operations and maintenance, and end-of-life treatment (Figure 7.1).

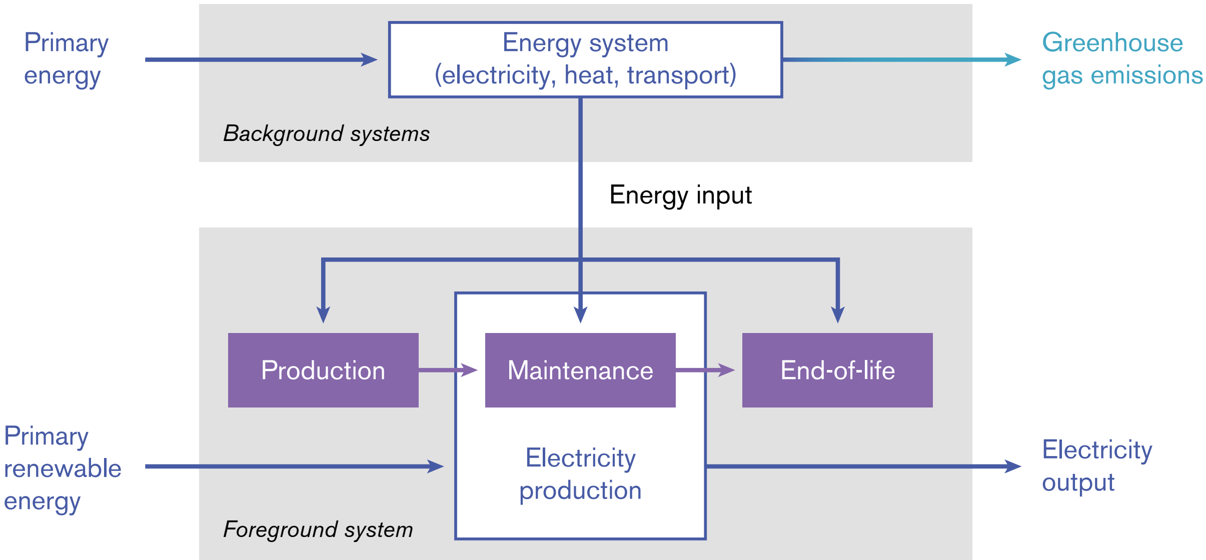

Figure 7.1 A simplified picture of the life cycle of a renewable power plant (purple) with associated energy flows (blue) and greenhouse gas emissions (teal). The system is subdivided into a foreground system and background energy systems.

An alternative indicator that conveys almost the same information is the *energy return on energy investment* (EROI). It compares the cumulative electricity output over the lifetime of the power plant to all energy input in production, maintenance and end-of-life treatment. In more complex systems with many parts with different lifetimes or when maintenance makes up a larger share of the energy input the EROI indicator may be preferable to the EPBT.

The direct primary renewable energy input in the power plant (low left corner in Figure 7.1) is not taken into account in the EPBT and EROI measures.[3] In contrast, a measure of *total system energy efficiency* would include both the direct energy input in power production as well as the more indirect life cycle energy inputs. Total energy efficiency would be a relevant measure in comparisons of different ways to convert a given resource.[4] One example could be a comparison between different means to convert a limited hydropower resource, and another could be

3 Similarly, the energy content of fuels directly combusted in fossil fuel-fired power plants are not included. See for example discussion in Raugei M, Fullana-i-Palmer P, Fthenakis V (2012). The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy Policy* 45:576-582.

4 See Kushnir, D. and Sandén, B.A., (2011). Multi-level energy analysis of emerging technologies: a case study in new materials for lithium ion batteries. *J. of Cleaner Production*, 19:1405-1416; and Rydh, C. J. and Sandén, B. A. (2005). Energy analysis of batteries in photovoltaic systems Part II. Energy return factors and overall battery efficiencies. *Energy conversion and management*, 46:1980-2000.

a comparison between solar cells and bioenergy systems that convert the solar energy hitting an area to electricity.

A generic problem in all energy analyses is to handle the fact that energy comes in different forms, mainly electricity, heat and various forms of chemical energy, e.g. gas, oil and coal. The value of different energy forms varies with application, e.g. liquid fuels are convenient in transport while computers are designed to run on electricity. Moreover, the conversion between forms entails different conversion efficiencies. It can be helpful to view the different energy forms as currencies. In the literature on EPBT, it is common to recalculate all currencies into one currency, most often something called 'primary energy'. In calculations of EROI, the conversion to a common currency is not always done, which creates some confusion.

Here we apply a common currency in calculations of both EPBT and EROI. We use electricity as this this common currency, since we believe electricity is a more well-defined currency than 'primary energy'.[5] In particular, it is straightforward to use in assessments of electrical power production technologies. To be clear we here use $EROI_{el\text{-}eq}$, as the ratio of the life-cycle electricity *output* to the sum of life-cycle energy *inputs* expressed in electrical energy equivalents.[6]

In life cycle assessments (LCA), which try to evaluate the environmental impact (e.g. contribution to climate change) of a product, service or technology, it is common to subdivide the system in foreground and background systems (Figure 7.1). The foreground system consists of the industrial processes that are defined and described specifically for the LCA study. These processes are usually directly linked to the assessed technology. The background systems comprise all other industrial processes, which would exist also without the assessed technology. Distinguishing the energy background system is of particular importance in assessments of climate impact of energy technologies since most of the impact stems from the background system, and this may vary between regions and change over time.

In particular it might seem unfair, or illogical, to allocate emissions from coal and natural gas to renewable power since these are the technologies the renewable power seek to replace. It has been suggested that when a technology in general, in contrast to particular plants, is to be evaluated, a 'net-output approach' can be used where the electrical input is deduced from the electricity output. However, when one seeks to estimate the side effects of building and operating renewable power plants in a specific year and location, emissions from the observed or forecasted energy background system need to be included in the assessment

5 While electric energy is the flow of electric charge, easily transferrable to many other energy forms (Chapter 2), 'primary energy' typically denotes naturally occurring energy sources. These may come in many different forms, ranging from solar radiation and the mechanical energy in winds, waves, streams and dams (Chapter 3), to the nuclear energy in uranium atoms and the chemical energy stored in coal, oil and natural gas. Since these forms of energy require different technologies for conversion into more well-defined energy carriers demanded in society, such as electricity and heat, with widely different conversion efficiencies (different exchange rates), 'primary energy' does not serve well as a common currency. In a system dominated by fossil fuels as primary energy, it makes some sense, but becomes less suitable in a system with high shares of different renewables.

6 See also Kushnir, D. and Sandén, B.A., (2011) and Rydh, C. J. and Sandén, B. A. (2005).

(see also Chapter 6 on the importance of differentiating between assessments of individual installations and generic technologies).[7]

In the LCA literature, a distinction is made between process LCA and input-output LCA. In the former type of study physical flows that can be allocated to the functional unit, in this context a kilowatt hour of renewable electricity, are defined and described bottom-up with process-specific information. One then needs to apply some cut-off rules, since if the machine that produced the machine and the electricity that powered the computer used by the executive officer in the factory that produced that machine etc. are to be included, the supply chains can become infinitely long. By using an economic input-output matrix this problem can be circumvented, as the input-output matrix covers the entire economy and include processes that are difficult to capture in physical terms such as services. On the other hand, one typically loses some detail with input-output LCA in comparison to process LCA. Hence, hybrid LCAs try to combine the best of both methodologies. In general, energy input and emissions tend to be higher in studies that apply input-output or hybrid LCA methodologies, as compared to those only applying process LCA.

ENERGY BALANCES AND CLIMATE IMPACT: CURRENT STATE-OF-THE-ART

Keeping in mind the theoretical background presented in the previous section, let us now move on to explore empirical evidence: What do state-of-the-art life-cycle assessments tell us about the energy balance and climate impact of renewable power?

There are numerous estimates of climate impact and energy balances in the literature. To be up to date, the results presented in this section are mainly based on life-cycle analyses from a recent study by the International Resource Panel.[8] The Resource Panel study presents comprehensive life-cycle assessments of power generation technologies that are either important causes of climate change or relevant for large-scale mitigation of climate change. Ocean energy results, here including tidal and wave power, are not available from the Resource Panel study and are adapted from other sources.[9]

Figure 7.2 compares estimated $EROI_{el\text{-}eq}$ and climate impact of different technologies. The ranges in results indicate variation among technological designs and regions defined in the Resource Panel study. Looking at the $EROI_{el\text{-}eq}$ results, one overall impression is that over their lifetime as producers of electricity, renewable

7 The net output approach was suggested by Hillman, K. M. and Sandén, B. A. (2008). "Time and scale in life cycle assessment: The case of fuel choice in the transport sector." International Journal of Alternative Propulsion 2(1): 1-12. A scenario approach with changing background systems over time was used in Arvesen, A. and Hertwich, E. G. (2011). Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment, *Environmental Research Letters* 6:045102.

8 Hertwich E.G. et al. (2014). The benefits, risks, and trade-offs of low-carbon technologies for electricity production. International Resource Panel, United Nations Environment Programme. In preparation.

9 Kelly K.A. et al. (2012). An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff–Weston severn barrage scheme. *Energy* 44(1): 692–701; Parker, R.P.M. et al. (2008). Energy and carbon audit of an offshore wave energy converter. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(8):1119-1130; Thomson, R.C. et al. (2011). Full life cycle assessment of a wave energy converter. *IET Conference Publications* 579; Woollcombe-Adams, C., Watson, C.M., Shaw, T. (2009) Severn Barrage tidal power project: Implications for carbon emissions. *Water and Environment Journal* 23(1):63-68.

power plants 'pay back' tens of times the energy costs of building and operating the plants. Further, according to these results, the $EROI_{el\text{-}eq}$ of renewable power is generally comparable to or greater than that of gas and coal power. Hydropower stands out in Figure 7.2 by exhibiting a much wider interquartile range and total range than the other technologies. The lower end of the spectrum for hydropower reflects that one of the included power plants is situated in a remote area and has large transport infrastructure requirements associated with it.

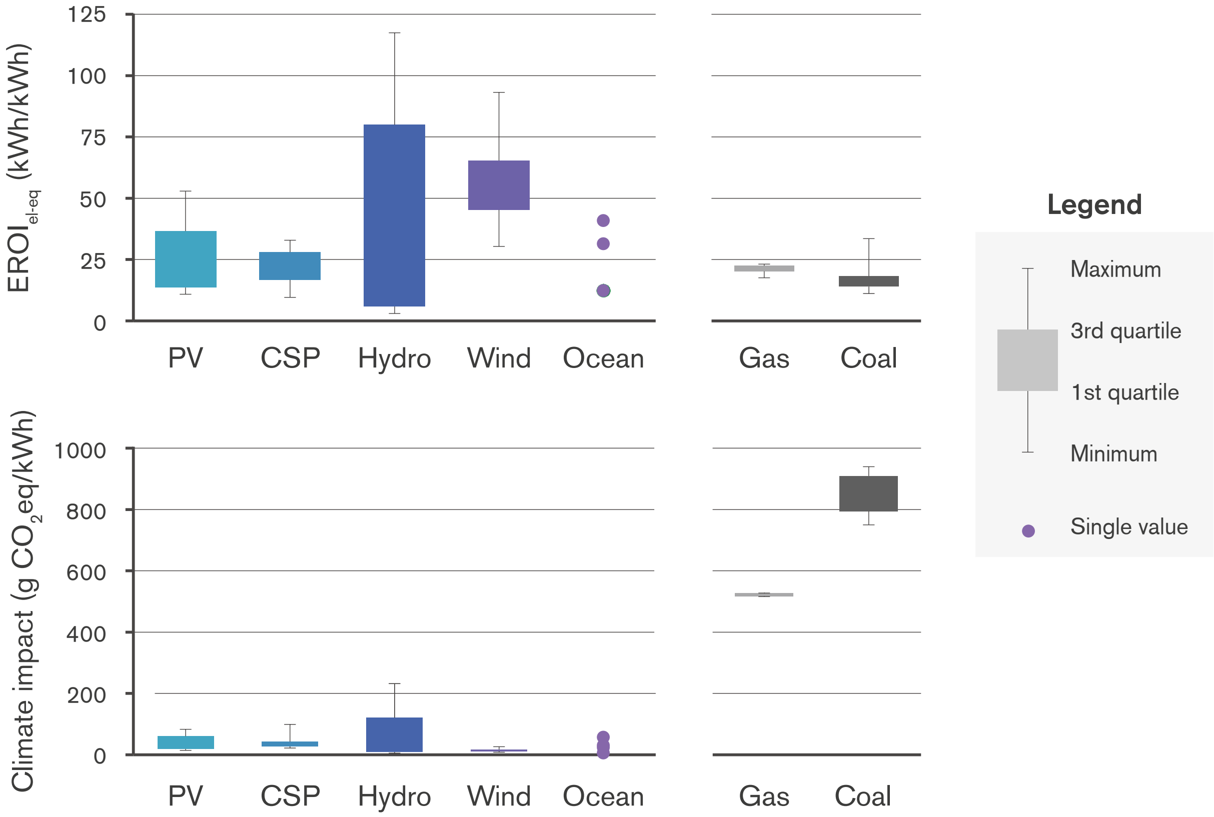

Figure 7.2 Energy return on investment (EROIel-eq) (upper panel) and climate impact (lower panel) for renewable and conventional fossil fuel power production. PV: solar photovoltaics. CSP: concentrated (thermal) solar power. Ocean comprises wave and tidal power. The fossil fuel systems are without carbon capture. A conversion factor 0.3 is used to convert energy contained in combustible fuels to electrical energy equivalent. Data sources: Hertwich E.G. et al. (2014), see Footnote 8; for ocean energy see Footnote 9.

As mentioned in the previous section, when we want to compare how efficiently a given resource is converted, the total energy system efficiency is a suitable measure. The large EROI values in Figure 7.2 indicate that the indirect life cycle energy input is small compared to the output and thus also to the direct energy input of primary renewable energy. Hence, for the total energy system efficiency, the direct conversion efficiency is in most cases a more important parameter than indirect life cycle energy requirement.

The most apparent example might be the comparison between direct solar and bio electricity. The direct conversion efficiency from solar energy to electricity is typically about hundred times higher in solar cells than in systems based on energy crops and combustion. For the total energy balance, it therefore does not matter much if the EROI is somewhat lower for the solar cells. If the bioenergy, hypothetically, would be produced without any energy input other than the solar influx on the field and if the solar cells would have an $EROI_{el\text{-}eq}$ in the lower end (say 10) the solar cell system would still be about 90 times more efficient and thus require a fraction of the land needed for the bioenergy system (see also Chapter 3 in this book and Chapter 5 in Systems perspectives on Electromobility).

The climate impact results in Figure 7.2 also place renewable power in a favourable light, with the interquartile ranges for solar, hydro and wind power being barely visible when plotted on the same scale as the climate impact of fossil fuel power. This indicates substantial mitigation potential if renewable energy sources replace fossil fuels in power generation. It may be noted that biogenic methane emissions from hydro power reservoirs is a concern for some regions of the world, especially when large areas are flooded.[10]

CHANGING BACKGROUND SYSTEMS

In the previous section we saw that greenhouse gas emissions of solar, hydro, wind and ocean power are low, but they are not zero. So, why are they not zero? It is because we need to rely on current industries to for example process materials, manufacture components and transport goods. How much fuel industries burn per unit of output differs appreciably between regions. Hence, background system characteristics can have significant bearing on LCA results. This is illustrated by the hypothetical example of polycrystalline silicon PV in Figure 7.3, where the variability in results is entirely due to regional differences in background systems.

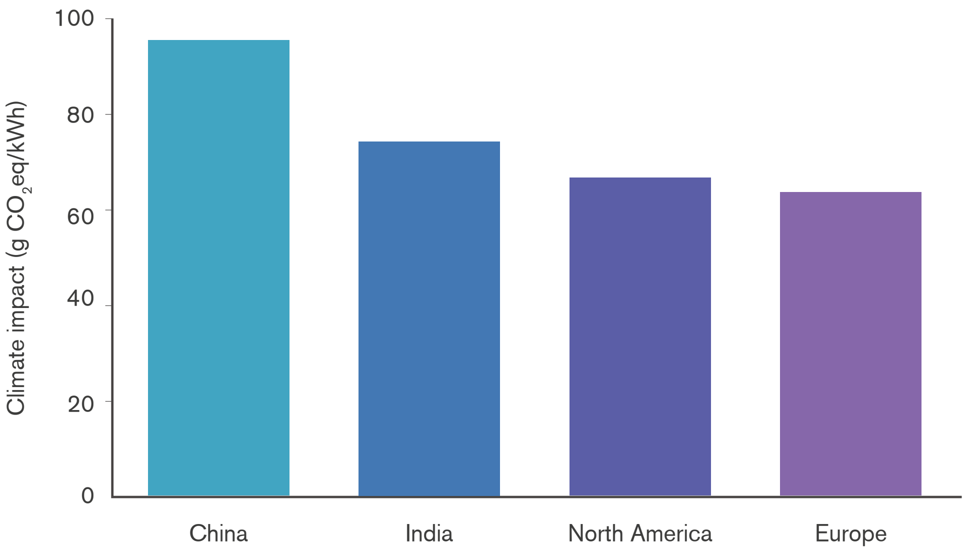

Figure 7.3 Climate impact of electricity from ground-mounted polycrystalline silicon photovoltaics, assuming identical foreground system and solar insolation value (2000 kWh/m²/year on tilted modules) for all regions. Data source: Adapted from the Resource Panel study.[11]

10 Hertwich, EG (2013) Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA. *Environmental Science & Technology* 47(17):9604-9611. See also Chapter 6.

11 Bergesen J. et al. (2014) Chapter 1. Photovoltaic power. In: Hertwich E.G. et al. (2014). The benefits, risks, and trade-offs of low-carbon technologies for electricity production. International Resource Panel, United Nations Environment Programme. In preparation

A significant share of the climate impact of renewable electricity is caused by fossil-fuel burning in power stations; that is, exactly the power stations that renewable power plants are meant to replace. Of course, emissions from power stations are real and need to be included in life-cycle assessments of *individual installations*, but at the same time one could argue that they are not an inherent property of renewable power as such, and should therefore not be included in assessments of the *technology in general*.

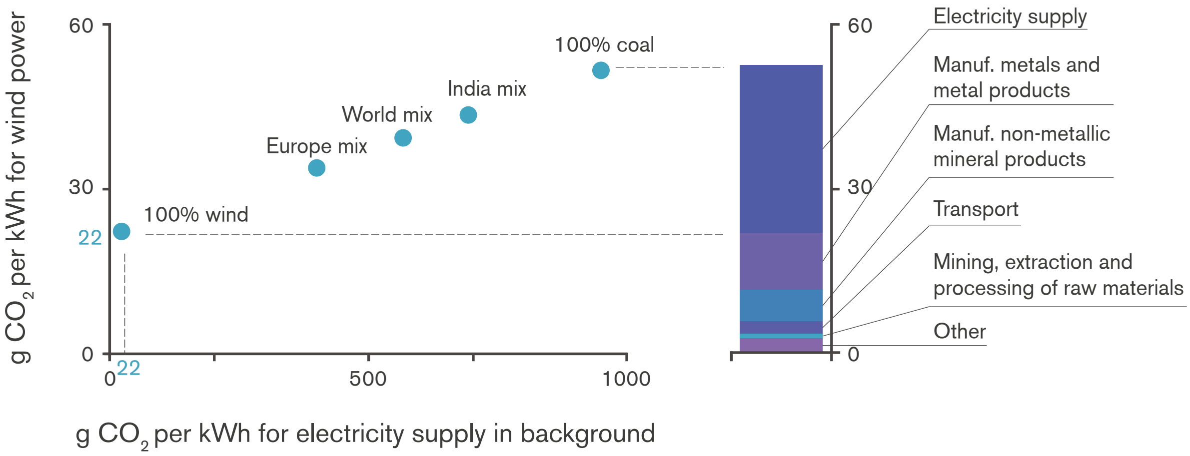

Figure 7.4 An illustrative example of the impact of background systems. The CO_2 intensity of offshore wind power (vertical axis) is plotted as a function of CO_2 intensity of background system electricity (horizontal axis). The stacked column shows the breakdown of CO_2 emissions by industries in a scenario where the background system uses coal as the only source of electricity. Source: Adapted from Arvesen et al. (2013).

To illustrate the role of the background electricity, we run an input-output-based LCA model for offshore wind power with different electricity mixes. This includes a scenario where, hypothetically, coal is the only source of electricity in the world, and one where offshore wind is the only source. In the latter case, a loop is created in the model so that the wind power that we study in the foreground system and the electricity that we model in the background system are essentially the same, hence corresponding to a net-output approach.[12]

As is evident from Figure 7.4, the CO_2 impact in the 100% offshore wind case is less than half of that in the 100% coal case. However, eliminating all direct emissions from electricity does not make offshore wind power CO_2-free, as 22 g CO_2/kWh is emitted in manufacturing, transport and other sectors (see the stacked column in Figure 7.4). In a prospective study of possible future systems the carbon intensity of these sectors may of course also decrease. In general, there may also be cases where the carbon intensity (or at least the energy intensity) of background activities increases in the future, for example as a result of generally declining metal ore grades and shift towards more remote ore deposits.[13]

12 The model is adapted from Arvesen A. et al. (2013) The importance of ships and spare parts in LCAs of offshore wind power. Environmental Science & Technology 47(6):2948-2956. A hybrid life-cycle analysis model is used in the reference, but for the sake of simplicity we here use a purely input-output-based model version with a one-region representation of the world economy. The approach taken in the all-wind case has been termed a 'net-output approach', since the electricity output that is required to produce wind power is deducted from the gross output, see Hillman, K. M. and Sandén, B. A. (2008).

13 See, e.g., Norgate, T. and N. Haque. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production* 18(3): 266-274; Mudd, G. M. (2010). The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* 35(2): 98-115.

CHANGING FOREGROUND SYSTEMS

As seen above, the choice of background systems for the production of electricity, transport and input materials is of critical importance for how much carbon dioxide emissions that are allocated to renewable power production. But not only technology background systems vary. Every class of technology (such as 'wind power' or 'PV') contains a wide span of different designs and every design might be produced in several ways and installed in areas with different conditions. This is less of a problem when a unique power plant is assessed, while it is a challenge when one aims at making claims about 'a technology' in general.

To capture the variation and a representative mean value of current systems one would ideally collect data from every producer in the world in a consistent manner. This is however not possible (partly due to trade secrets), and maybe not even worth the effort. What might be more interesting from a strategic point of view is to capture systematic variation within technology groups. Figure 7.5 provides one such example of the effect of scale on the carbon dioxide intensity of on-shore wind power. In the lower end of the turbine size spectrum, the carbon dioxide intensity decreases markedly with scale. The evidence in Figure 7.5 is inconclusive for the megawatt turbine size range however (there are too few data points).

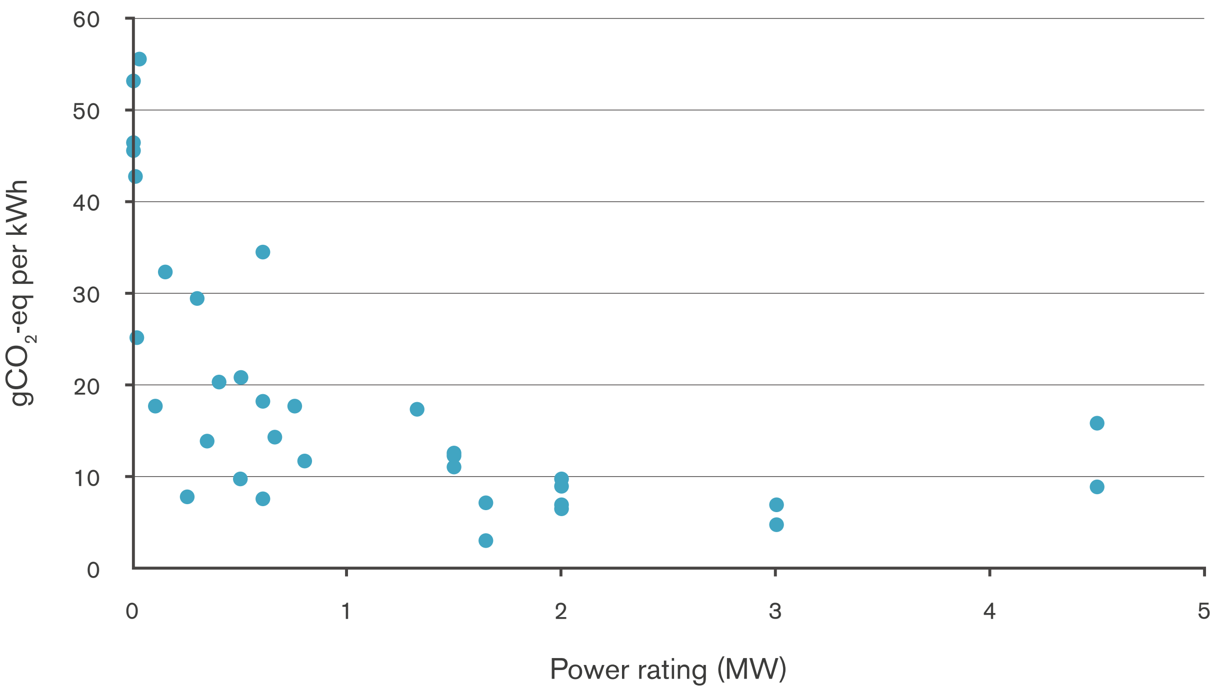

Figure 7.5 Climate impact of on-shore wind power related to power rating of the turbine (process LCA). Source: adapted from Arvesen and Hertwich (2012).

Another important observation is that the required energy input (and thus also the related climate impact) may change over time. An example of a drastic reduction of EPBT and the related increase of EROI is provided in Figure 7.6. The EPBT of PV systems decreased from 20-40 years in the early 1970s to about one year in 2011. This implies that the EROI over the same period increased from about one to 20-40. While the quality of data and assessment methodology clearly has improved over time, the trend can mainly be attributed to the growing production volumes that have allowed for efficiency improvements due to the accumulation of experience and knowledge and realisation of economies of scale in production. In 2011, the market for PV was more than 100 000 times larger than in 1975.

Prospective numbers for 2020 (see Figure 7.6) indicate that the trend towards higher EROIs may continue. Figure 7.6 also shows that thin-film PV tends to have a higher EROI than traditional crystalline silicon PV. A technology shift towards thin-films could thus increase the overall EROI of PV.[14] A conclusion we may draw is that claims about the feasibility of a technology based on old data may be of little value, and even up-to-date data for current production might be of limited value when it comes to foresee the energy balance and climate impact of future systems.

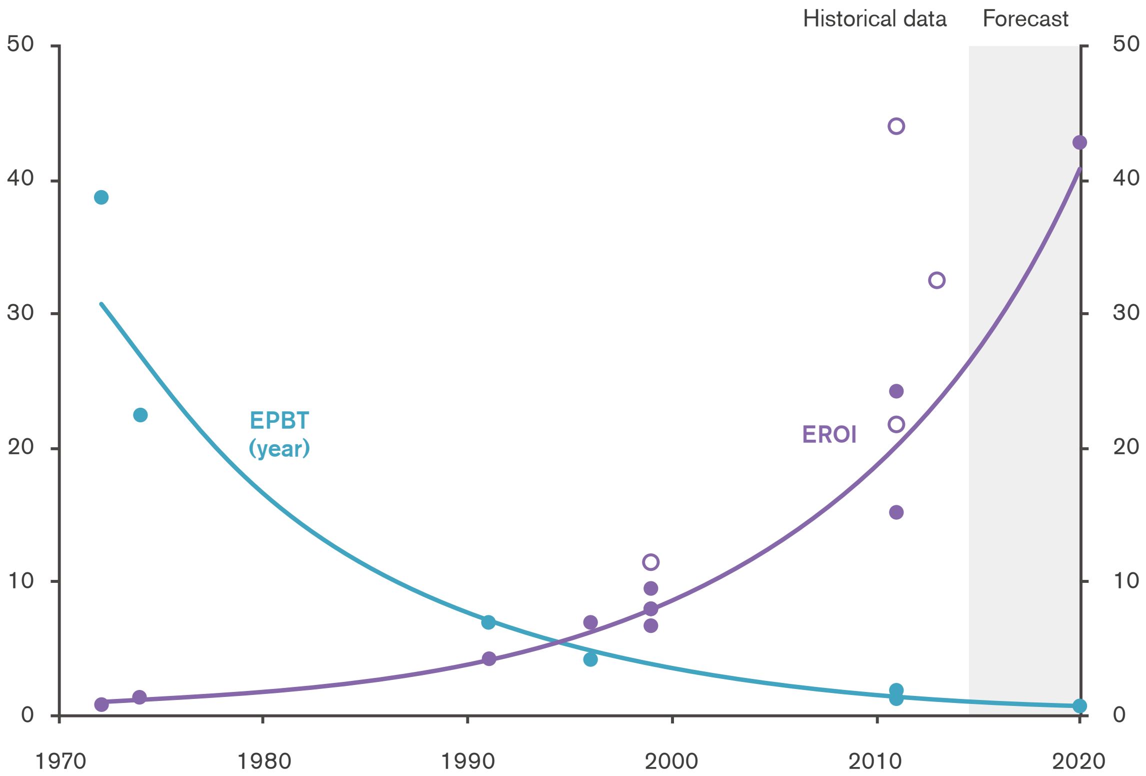

Figure 7.6 The development of energy payback time (EPBT) and energy return on energy investment (EROI) of PV systems over time. The solid and empty dots represent crystalline silicon and thin film technology, respectively. The value for 2020 is a forecast received from a design study. The trend lines are best fit exponential curves of historical data for crystalline silicon. A solar insolation of 1700 kWh/m^{2}yr is used for all values and a lifetime of 30 years is used to calculate EROI values.[15]

14 One study has daringly suggested that the EPBT for novel plastic PV technologies may need to be measured in days, instead of months or years. These may however have shorter lifetimes and thus the corresponding increase of EROI is lower (Espinosa, N., et al., 2012. Solar cells with one-day energy payback for the factories of the future. Energy & Environmental Science 5(1): 5117-5132). It may also be noted that potential future shortages of supply of certain metals (e.g., tellurium and indium) used in some (but not all) thin-film PV could place a limit on the future market uptake of such technologies or decrease EROI due extraction from low grade ores, see e.g. Andersson, B. A. (2000). Materials availability for large-scale thin-film photovoltaics. *Progress in Photovoltaics* 8: 61-76; Graedel, T. E. and L. Erdmann (2012). "Will metal scarcity impede routine industrial use?" MRS Bulletin 37(04): 325-331.

15 Historical data: Wolf M. (1972). Cost goals for silicon solar arrays for large terrestrial photovoltaics. In: Proceedings of 9th IEEE PV specialist conference, Silver Spring, MD. pp. 342–50; Wolf M. (1975). Cost goals for silicon solar arrays for large terrestrial photovoltaics – Update 1974. Energy Conversion 14:49-60; Baumann, A. E., et al. (1997). Environmental impacts of PV systems-ground-based vs. BIPV. Twenty-Sixth IEEE Photovoltaic Specialists Conference, pp 1361 - 1364; Alsema, E. A. (2000). Energy pay-back time and CO_2 emissions of PV systems. *Progress in Photovoltaics: Research and Applications* 8(1):17-25. De Wild-Scholten, M. J. (2013). Energy payback time and carbon footprint of commercial photovoltaic systems. *Solar Energy Materials and Solar Cells* 119: 296-305; Prospective study: Mann, S. A., et al. (2013). The energy payback time of advanced crystalline silicon PV modules in 2020: a prospective study. *Progress in Photovoltaics: Research and Applications*.

The trend in Figure 7.6 can mainly be attributed to falling energy requirements of the PV modules, and less to reduced requirement of other system components. A consequence of this is that substructures will be of increasing importance for ground mounted systems, and in small roof-top systems, components such as inverters will likely be responsible for an increasing share of the energy input.

This leads to the next important issue: location. Due to variation in natural conditions and availability of complementary technical infrastructure, the energy balance will differ between locations.

Differences in the density of renewable energy flows have a large impact on the EPBT and EROI of renewables. The solar energy influx varies by about a factor of two over most parts of the world (see Figure 3.1 in Chapter 3). Thus the EROI of a PV system in Sweden would be about half that of a system in northern Africa (the numbers in Figure 7.6 is calculated from an irradiance representative for southern Europe, close to the world average for horizontal surfaces). The wind energy resource is more variable than solar energy and all other renewable energy flows have an extreme geographical variability (Chapter 3 and 4). For example, trying to make use of a tidal resource where the tide hardly is noticeable or hydropower where the land is more or less flat would entail very low EROI values.[16]

It is not just the energy density which varies across locations, but also distance to existing infrastructure and other site characteristics influencing material and energy requirements. PV integrated in buildings requires no other substructures while ground mounted systems in open areas normally require some additional construction work. PV at sea might in turn require new types of substructures and maintenance. A comparison of on-shore and off-shore wind power shows that the higher electricity production at sea is more or less balanced with higher energy costs for construction and maintenance.

The fact that all locations are not equal should at some point in time start to have a negative effect on the energy balance. First the good spots are taken; then lower quality resources in more complicated environments will be used. Decreases in EROI can also conceivably occur as public resistance towards renewable power hinder exploitation of sites that are optimal from a resource or technical point of view. This effect should still be fairly small for most renewable energy sources since only a fraction of the potential is utilised (Chapter 3). Hydropower might be an exception, since most good sites and a large fraction of the technical potential is already used (Chapter 3 and 6). Another example might be the current development of offshore wind power in Europe; the average distance to shore for new projects was 14 km in 2009 and 29 km in 2012, and both distance to shore and water depth are on the whole expected to increase in coming years.[17] For solar power the argument might be of less relevance since the resource is so evenly distributed across the globe in abundant quantities (Chapter 3).

16 However, as stated in the introduction to this chapter there may be niche applications where the energy balance is of less importance, and the crucial thing is to produce some electricity from the resources that happen to be locally available.
17 EWEA (2013). The European offshore wind industry - key trends and statistics 2012.

A related aspect, which goes beyond the scope of this chapter, is the varying need for enhanced grid infrastructure (Chapter 9), flexible operation of fossil fuel power plants (Chapter 11) or energy storage (Chapter 5 and 12) to accommodate intermittent renewables in the electric system, and the energy use and greenhouse gas emissions connected with such grid and balancing requirements.

CONCLUDING REMARKS

While historical data for some technologies indicate that worries might have been warranted in the past, we can conclude that there is now less cause for concern about greenhouse gas emissions and energy payback of renewable power technologies in general. Replacing conventional fossil fuel-based power plants with renewable power offers substantial reductions in greenhouse gas emissions. The energy return on energy investment is now at least as high for renewables as for conventional fossil fuel-based power plants. With lower greenhouse gas intensities of energy background systems and development of foreground system components and production processes, it is likely that the climate impact will decrease in the future. It is also likely that technology development will continue to improve the energy balance of most renewable power technologies.

However, it is possible to construct systems with low energy return on energy investment and high climate impact. With large scale implementation of the less abundant renewables, the energy return may decrease as lower quality resources in more complicated environments are used. Moreover, new requirements of electrical grids and energy storage systems are not considered in this assessment and, depending on system configuration, these components may add a significant energy burden. Hence, we consider it still worthwhile to assess individual projects and follow the general trends.

8

WILL OCEAN ENERGY HARM MARINE ECOSYSTEMS?

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INTRODUCTION

Human activity tends to excavate the natural capital and degrade the ecosystem services on which civilization depends. For long-term sustainability a more proactive resource management is needed.[1] Since natural and social systems are complex, environmental impacts of new technologies can be very difficult to predict beforehand, but once technical systems have spread and have become widely accepted they tend to be hard to control. Will ocean energy development be a safe path towards sustainable power production, or will it inflict additional burden on already deprived marine life? In this chapter it will be argued that the answer is much dependent on adaptive engineering and prospective planning.

AN OCEAN FULL OF ENERGY

Ocean energy targets energy from within the ocean and commonly refers to tidal current energy, wave energy, ocean current energy, and ocean thermal energy conversion (OTEC), see Figure 8.1.[2] Although some full-scale devices have been deployed, ocean energy is not yet technically mature and fully commercial installations are yet to be installed (Chapter 4). While there are diverging views on the potential contribution of ocean energy to global power generation, it seems clear that in specific geographical areas ocean energy may contribute significantly to electricity supply, with expected commercial breakthroughs beyond 2020 (Chapter 3).[3]

1 MEA (2005). Ecosystems and Human Well-being: Synthesis. Millennium Ecosystem Assessment, Island Press, Washington DC.

2 Ocean energy also comprises salinity gradient energy and tidal barrages but these technologies have not been included in this chapter as they seemingly are farther from expansive growth.

3 Esteban, M. and Leary, D. (2012). Current developments and future prospects of offshore wind and ocean energy. *Applied Energy,* 90, 128-136. See also Chapter 3.

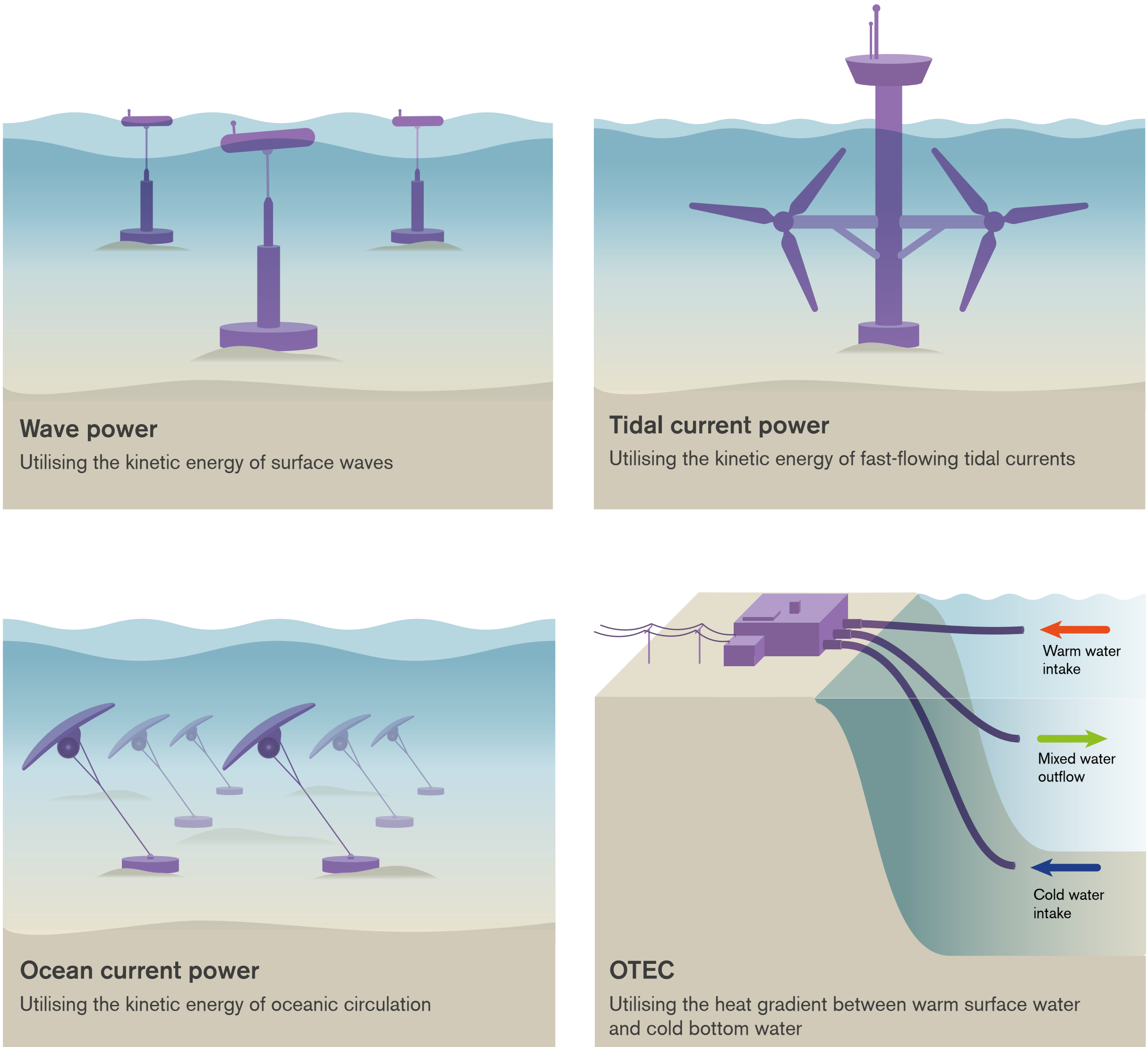

Figure 8.1 Conceptual illustrations of ocean energy technologies. Arrows indicate water flow directions. The illustrated technologies are not-to-scale examples of a large number of prototypes under development.

To large extent the extractable resource potential is limited by environmental considerations such as the risk of affecting ocean circulation patterns and local oceanography. Ocean energy resources are available across the globe, including both developing countries with rampant energy demand and industrialised countries in need of diversifying power generation.[4] Northern North America, north-western Europe and East Asia have plenty of tidal energy hotspots. West-facing coasts in the northern hemisphere and east-facing coasts in the southern hemisphere are typically exposed to high wave power. Many tropical islands and coasts with narrow continental shelves, particularly in western parts of the Pacific Ocean, have optimal conditions for OTEC technology (Figure 3.4). Should the future hold a serious utilisation of these potential power sources, ocean energy installations would become common at many locations and, as any marine activity, to some level affect marine ecosystems.

4 WEC (2010) 2010 Survey of Energy Resources. World Energy Council, London.

AN OCEAN UNDER PRESSURE

Since prehistoric time humans have used the ocean for food and transport. By the time of the industrial revolution the ocean had played a major role for trade and economic growth, but pressure on the marine ecosystems was still limited and spatially confined. It was with the introduction of steam and later combustion engines in ships and fishing vessels that pressure intensified. By 1950, several fish stocks were overexploited and whale stocks collapsed on a global scale. Post World War II a tremendous intensification of fishing was made possible by new technologies such as the sonar systems and satellite navigation, and by governmental subsidies of fisheries. Moreover, offshore oil extraction, aquaculture, and coastal recreation added to ecosystem pressure along with marine pollution and nutrient rich agricultural runoff to coastal ecosystems. Around the millennium shift a third of the global fish stocks were overexploited or even collapsed; 90% of large predatory fish had disappeared; more than 40% of all coastal seas were heavily affected by human activity; and throughout the world there were no longer any unaffected corners of the ocean.[5]

Due to the 'shifting baseline' phenomenon[6] there is no longer a common memory of how many and how large fish that could be caught by the nearby beach a few decades ago and pristine marine ecosystems are no longer reference points. Unfortunately, there is little reason to believe that this degradation will come to a halt anytime soon.[7]

This is the background we have to keep in mind when trying to assess what would be the consequences of introducing ocean energy technologies. As will be discussed, the full effect of ocean energy or any other potential stressor to the environment can only be grasped with consideration of food-web interactions and cumulative effects. However, first we need to understand the direct environmental impacts of different ocean energy technologies.

ECOLOGICAL IMPACTS OF OCEAN ENERGY – WHAT DO WE KNOW?

Given that ocean energy is in such an early phase there is still a scarcity of scientific knowledge regarding its environmental effects. While some potential impacts are technology-specific, others are general and can be foreseen by considering effects of existing marine activities. Figure 8.2 illustrates the potential stressors from the ocean energy systems considered here, together with stressors from some other marine and coastal activities. Below follows a synthesis of the current understanding of environmental effects from ocean energy.

Offshore installations – ocean energy or other – mean that new hard substrate is introduced and that part of the previous habitat is removed. The new substrates of steel or concrete will be colonised by some species on the cost of species that prefer soft bottoms like mud and sand. In general, hard substrates are rare in marine ecosystems and in some areas natural hard substrates have been removed by years of trawling. The introduction of hard substrates, even if being artificial, can

5 Smith, H.D. (2000). The industrialisation of the world ocean. *Ocean & Coastal Management,* 43, 11-28; Halpern, B.S. et al. (2008). A Global Map of Human Impact on Marine Ecosystems. *Science,* 319, 948-952, Jackson, J.B.C. (2008). Ecological extinction and evolution in the brave new ocean. *Proceedings of the National Academy of Sciences,* 105, 11458-11465.

6 Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology & Evolution,* 10, 430.

7 Jackson, J.B.C. (2008); Pitcher, T.J. and Cheung, W.W.L. (2013). Fisheries: Hope or despair? *Marine Pollution Bulletin,* 74, 506-516.

often be considered beneficial. For instance, it is shown that many fish, crayfish, and molluscs thrive at offshore wind power foundations where they find food and protection.[8] It is likely that analogous ocean energy foundations will have similar beneficial effects.

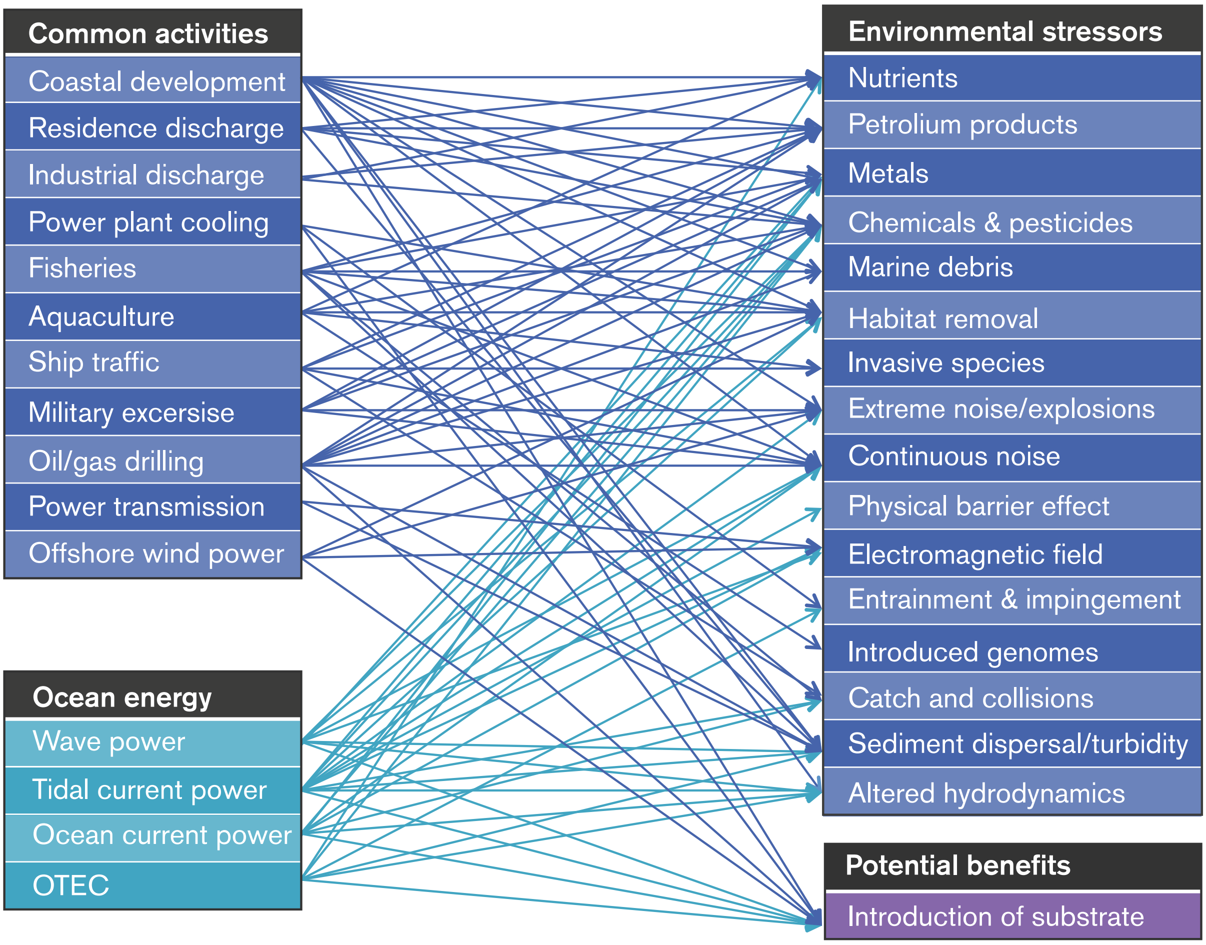

Figure 8.2 Environmental stressors and potential ecological benefits caused by some common marine and coastal human activities (blue arrows) and as proposed for ocean energy technologies (teal arrows). The illustration intend to broadly depict the situation of many concurrent activities inflicting similar stressors to the marine environment.

Noise emissions from operating turbines can be detected by fish and marine mammals. Tidal current turbines emit more noise (160-180 dB re 1 μPa at 1 m) than offshore wind power (130-150 dB re 1 μPa at 1 m) but less than cargo ships (185-195 dB re 1 μPa at 1 m). Wave power and OTEC are expected to emit lower noise levels (<140 dB re 1 μPa at 1 m). It has been argued that the noise from ocean energy and offshore wind power under certain conditions and for some species can cause stress and masking of animal communication.[9] Behavioural changes have been observed in laboratory experiments where animals were exposed to playback of noise corresponding to that created by turbines at a distance of about

8 Reubens, J. et al. (2010). Chapter 6. The importance of marine wind farms, as artificial hard substrata, for the ecology of the ichthyofauna. *Offshore wind farms in the Belgian part of the North Sea: early environmental impact assessment and spatio-temporal variability* (eds S. Degraer et al.), pp. 69-82. Royal Belgian Institute of Natural Sciences, Brussels; Andersson, M.H. (2011). Offshore wind farms - ecological effects of noise and habitat alternation on fish. Doctoral thesis, Stockholm University; Bergström, et al. (2013). Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Mar Ecol Prog Ser,* 485:199-210.

9 Slabbekoorn, H. et al. (2010). A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology and Evolution,* 25:419-427.

ten metres, but empirical evidence from the field is still inconclusive. A recent study shows that codfish are in good health around offshore wind power foundations and any negative impacts from operational noise are likely to be small and subtle.[10]

Other generic stressors from offshore installations are construction-related noise, dredging, and electromagnetic fields from power transmission. There is substantial evidence showing that pile-driving, which is used for mooring of for example tidal current turbines, can have detrimental impacts on individual fish and marine mammals.[11] Pulses of extreme sound may damage the swim bladder and hearing organs at a close distance, and the pulses can be detected by the animals over a distance of tens of kilometres. Dredging, if carried out in fine-grain sediment, may clog the gills of fish and reduce the survival among fish eggs and larvae. Effects of electromagnetic fields have been less studied, but fields from ocean energy cables can be detected by highly specialised animals like eels and elasmobranchs (sharks and rays). For these animals unburied cables may cause disorientation or disturbed forage behaviour. All the above mentioned stressors can to some degree be mitigated, for instance by choosing an appropriate foundation concept, by dampening pile-driving, by using silt curtains to reduce sediment dispersal, or by burying transmission cables so that the electromagnetic fields not reach out to the water. In addition, impacts to particular ecological values (e.g. endangered species) can sometimes be avoided simply by scheduling construction events out of biologically sensitive periods, such as spawning and migration seasons.[12]

Wave power is often considered environmentally benign and hitherto there are no studies indicating detrimental environmental impacts from the – very few – devices that have been in operation. It has however been postulated that floating wave power buoys may attract migrating and foraging birds and may, especially in rough sea conditions, entangle marine mammals. If wave power devices do affect the movability of birds and mammals, large wave power farms may have an impact on their migratory routes. Other possible effects of wave power concern dampening of local wave climate, affecting the vertical mixing of water and sediment transport and coastal erosion. This concern is site dependent as the beach morphology at many typical wave power locations is continuously shifting due to natural wave exposure variation. Therefore, wave power impact on erosion would not always be of concern.

Some *tidal current turbines* have rotor blades moving at speeds above 10 m/s through turbid waters with low visibility. This rotor speed is fast in relation to the swimming speed of most marine mammals, diving birds and fish and collision risks have been much discussed but rarely investigated. A recent study of daytime effects of a small tidal turbine on fish showed that all present fish avoided collision with the rotor and that there was a general decrease in the number of fish passing through the near-field of the rotor compared to fish movements through

10 Reubens, J.T. et al. (2013). Offshore wind farms as productive sites or ecological traps for gadoid fishes? – Impact on growth, condition index and diet composition. *Marine Environmental Research,* 90:66-74.

11 Popper, A.N. and Hastings, M.C. (2009). The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology,* 75:455-489.

12 Hammar, L. et al. (2008). Adapting offshore wind power foundations to local environment. pp. 87. Vindval, The Swedish Environmental Protection Agency; Hammar, L. et al. (2014). Assessing ecological risks of offshore wind power on Kattegat cod. *Renewable Energy,* 66:414-424.

the same place when the rotor was removed.[13] It was shown that small reef fish dared to pass close to the rotor while large predatory fish kept a larger distance from the rotor. A study at another turbine, similar in size and design but differently positioned, showed that some small fish were swept into the turbine while others managed to swim away.[14] The amount of fish failing to avoid the turbine was larger during the night than during the day, indicating that avoidance success is related to water visibility. When it comes to large tidal turbines collisions is likely more difficult to avoid for the animals but no empirical studies have been presented. Probabilistic models of collision risks around large tidal turbines raise concerns though, as substantial losses of fish and marine mammals due to collisions have been calculated.[15] But since these probabilistic models do not account for active avoidance manoeuvres among the animals, the alarming results are likely to be exaggerated. Field observations of fish fauna in strong currents also indicate that the number of fish is low in the strongest currents, where turbines would be operating. Research and monitoring on animal behaviour around tidal turbines are needed. But even if collisions are rare, large tidal power arrays may have a barrier effect on large animals and multiple-turbine installations should therefore be designed with apposite migration passages between turbines.

Large tidal current power installations may also affect local hydrodynamics and thus the sediment characteristics in the area. Such alternation of hydrodynamic regimes could have large ecosystem effects and must be avoided.[16] For this and technical reasons it is usually suggested that tidal power should not extract more than about 10% of the natural flow at a given location.

Ocean current power target slower currents and deeper water than tidal power (Figure 3.2). Most turbines therefore resemble tidal current turbines, but of much larger size. Consequently, the ocean current turbines are subject to similar collision risk principles as for tidal current power. But even though the rotor blades are large the slower ocean currents ensure that most vertebrate animals will have great chance to swim away from the hazard. An interesting and different ocean current power development is the Deep Green[17] device, where a 12 m wide underwater kite carries the turbine in a trajectory transverse to the current in order to increase the water flow over the rotor. The response and ability of avoidance among fish and marine mammals approaching such a device have not yet been investigated and the uncertainties are worrisome.

Ocean Thermal Energy Conversion (OTEC) has been tested at small scale and larger plants are projected at several locations but due to the high investment costs no commercial power plants, or power plants larger than 1 MW, have yet been constructed. OTEC power plants utilise the vertical heat difference of tropical seas to produce power as well as desalinated water. This is made possible by heat exchange technology using large amounts of water from the cold deep sea

13 Hammar, L. et al. (2013). Hydrokinetic Turbine Effects on Fish Swimming Behaviour. *PLoS ONE,* 8:e84141.
14 Viehman, H.A. (2012). Fish in tidally dynamic region in Maine: Hydroacoustic assessments in relation to tidal power development. MSc, The University of Maine.
15 Wilson, B. et al. (2007). Collision risks between marine renewable energy devices and mammals, fish and diving birds - Report to the Scottish Executive. Scottish Association for Marine Science, Oban; Hammar, L. and Ehnberg, J. (2013). Who should be afraind of a tidal turbine - the good, the bad or the ugly? *10th European Wave and Tidal Energy Conference.* EWTEC, Aalborg.
16 Shields, M.A. et al. (2011). Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment. *Ocean & Coastal Management,* 54: 2-9.
17 The Deep Green turbine is developed by Minesto. See Minesto (2014).

and the warm surface and a working fluid that is vaporised and forced through turbines. The water intake of a 100 MW OTEC plant would be about 300 and 400 $m^3 s^{-1}$ at deep sea and surface respectively (for comparison the cooling water intake of a 1 GW nuclear power plant is about 75 $m^3 s^{-1}$). The number of entrained and impinged organisms can therefore be large. While such damage could be mitigated by effective screens around the intake pipes it is considered more difficult to prevent entrainment of planktonic eggs and larvae. Thus substantial losses of various recruits are expected and have been shown during pilot plant experiments.

Another possibly severe environmental impact from OTEC is the alternation of hydrological conditions, such as changes in temperature, acidity and salinity, and increase of nutrients in the surface water due to mixing with nutrient rich deep water. Increase of nutrients can lead to eutrophication which in oligotrophic tropical ecosystems can have detrimental effects on important coastal ecosystems such as coral reefs and seagrass beds. If the OTEC discharge water is released at a sufficient depth such effects can be avoided, at the expense of higher installation costs.

In summary, some ocean energy technologies raise more environmental concerns than others. To the current level of understanding it seems reasonable to believe that wave power and small-scale tidal current devices are unlikely to have negative environmental impact while the benevolence of large scale tidal power, ocean current power, and OTEC will be much depending on design and local ecological conditions.

WHAT TO DO WITH THE UNKNOWNS?

As discussed above there are still many unknowns related to the potential environmental effects from ocean energy. Because awareness of environmental issues is more developed now than it was when earlier marine activities were introduced in the ocean, the many unknowns about environmental impacts of ocean energy pose a barrier for achieving legal consent. The precautionary principle often implies that developers need to show with confidence that significant impacts will not occur. This requires either extensive applied research or long-term monitoring. Among ocean energy developers this is often considered a difficult quandary to overcome in the early phase of technical development. Therefore, the ability of making robust environmental impact assessments despite incomplete information is important.

On the project level, existing knowledge on analogous stressors can be used to predict the effects from new stressor sources (here: ocean energy technologies) by applying for instance weight-of-evidence methodology.[18] Weight-of-evidence imply that hypothetical cause-effect chains, that is, how ocean energy devices possibly can cause effects on ecological receptors, are described on the basis of arguments referring to experience from other stressors (e.g. shipping or offshore wind power). These arguments are graded on the basis of their scientific foundation. Then contradicting arguments, advocating that there is no cause-effect relationship, are added and similarly graded. By comparing the reliability among arguments it can be concluded whether a cause-effect relationship is likely, unlikely or still undecided. Each cause-effect relationship will also be assigned

18 Hammar, L. et al. (2014). Assessing ecological risks of offshore wind power on Kattegat cod. *Renewable Energy*, 66:414-424.

with a maximum temporal and spatial range that can be used to calculate the worst-case magnitude of effect.

A more quantitative approach to assessment uncertainties is to model potential impacts using Monte-Carlo simulations, where probabilistic distributions of unknown parameters are assigned instead of arbitrary means. This method allows for an assessment output with confidence intervals, though some level of understanding of the input parameters is of course required.

Once a quantity of effected environmental receptors has been estimated it is important to relate this effect magnitude to population dynamics for an understanding of how important the effect may be. For example, the removal of tens of thousands of herrings or hundred acres of soft bottom habitat may under some conditions not lead to detectable population or ecosystem effects while in another case the removal of only tens of specimens from large and endangered animals or the removal of a few acres of coral reef bottom may have large population level and ecosystem impacts. The ecological risk assessment framework can be useful here, as it separates between "what can happen?" and "how bad can it be?".[19] The ecological risk assessment framework is a transparent assessment method used within a variety of scientific fields including impacts from ocean energy.

At the strategic level, uncertainties can be reduced by applied research, in particular through rigorous monitoring[20] programs. Such undertakings are often costly for early-stage developers. Here it is important that pilot plants and, subsequently, full-scale plants are allowed to operate under intended conditions so that actual impacts are revealed. For instance, monitoring efforts at the UK based tidal turbine Seagen were of little value for a long time since the turbine was shut down when marine mammals approached the site. Only when effects are revealed and quantified appropriate mitigation measures can be developed.

A WIDER SYSTEM PERSPECTIVE

As mentioned earlier in this chapter it is not the isolated stressors of an ocean energy installation that determine environmental impact, but the combined effect of those stressors and the concurrently prevalent stressors from other human activities. This cumulative effect is what really matters for the ecosystem, but also proves quite difficult to estimate. Cumulative effects can be simply additive, synergistic (one stressor increasing the effect of another stressor) or antagonistic (one stressor reducing the effect of another). For instance, on the population level the loss of fish from collision with tidal turbine rotors would be additive to fish losses due to fishing; nutrient enrichment from incautiously designed OTEC discharge would likely be synergetic to global warming induced coral bleaching; and the provision of new habitats around ocean energy foundations would perhaps act as antagonistic to effects from other human activities such as fishing or coastal development. While the current understanding of cumulative effects is incomplete

19 Suter, G. (1993). Defining the Field. *Ecological Risk Assessment* (ed. G. Suter). Lewis Publishers, Michigan; Biddinger, G.R. et al. (2008). Managing Risk to Ecological Populations. *Population-Level Ecological Risk Assessment* (eds L.W. Barnthouse et al.), pp. 7-39. SETAC Press, Pensacola, US.

20 Crain, C.M. et al. (2008). Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters,* 11:1304-1315; Halpern, B.S. et al. (2008) Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean & Coastal Management,* 51:203-211.

and effects are difficult to quantify, it is still important be aware of and to consider at best practise.

The existence of multiple concurrent stressors and cumulative effects should not be interpreted as arguments for preventing growth of ocean energy in general. As long as preventative measures are taken along with ocean energy deployment, most ecological receptors are likely to be under heavier pressure from other human activities than from these new technologies. A shift from a management regime of many project-based assessments to more holistic marine spatial planning, where all uses of ocean resources are considered and regulated together, will not only benefit the marine environment but may also allow for ocean energy developments. Such management shift is currently underway in many parts of the world.

In the context of holistic assessment it is also important to understand the interactions within the marine food web. For instance, if top predators like marine mammals are affected positively or negatively by an ocean energy installation this will have an effect on other organisms in the food web. For instance, a reduction of porpoises may enhance the number of porpoise prey while a potential attraction of seals would reduce the number of seal prey (and potentially also reduce fish fitness through spreading of seal-fish hosted pathogens). As another example, nutrient enrichment from incautiously designed OTEC plants would affect the whole food web, potentially leading to shifts in entire ecosystems. More nutrients mean growth of algae, in turn shading and outcompeting corals and seagrass meadows, ultimately leading to altered and possibly irreversibly changed ecosystems. Moreover, potential barrier effects of tidal power arrays could lead to impaired fish migration and loss of habitat connectivity.[21] While holistic approaches to assessment and management are rare in practice they are highly necessary given the inevitability of accelerated utilisation of ocean resources – ocean energy and others.

ENVIRONMENTAL IMPACT DEPENDS ON MANAGEMENT

In conclusion, there are still many unknowns regarding direct environmental impacts from ocean energy, where some technologies seem to have limited negative effects and others give rise to more concern. It is even possible that ocean energy in many cases may act more positively than negatively on marine ecosystems, given the protection against destructive fishing methods in combination with the introduction of hard substrate habitats that benefits many species.[22] Altogether, the potential damages and benefits from ocean energy to marine ecosystems are dependent on whether hazards from particular technologies can be mitigated and if synergistic cumulative effects from ocean energy and other human activities can be avoided.[23] In short, the environmental benevolence of ocean energy depends on the level of adaptive engineering and considerate planning.

21 Hammar, L. et al. (2013). Hydrokinetic Turbine Effects on Fish Swimming Behaviour. *PLoS ONE,* 8:e84141.
22 Inger, R. et al. (2009). Marine renewable energy: potential benefits to biodiversity? An urgent call for research. *Journal of Applied Ecology,* 46:1145-1153; Wilhelmsson, D. et al. (2010). Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy. pp. 102. IUCN, Gland; Langhamer, O. (2012). Artificial Reef Effect in relation to Offshore Renewable Energy Conversion: State of the Art. *The Scientific World Journal,* 8; Bergström, L. et al. (2014). Effects of offshore wind farms on marine wildlife–a generalized impact assessment. *Environmental Research Letters,* 9:034012.
23 Boehlert, G.W. and Gill, A.B. (2010). Environmental and ecological effects of ocean renewable energy development: A current synthesis. *Oceanography,* 23:68-81.

9

CHALLENGES OF INTEGRATING SOLAR AND WIND INTO THE ELECTRICITY GRID

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INTRODUCTION

The main purpose of the electricity grid is to transport electricity from generation sites to consumption sites. As discussed in Chapter 2 and 5, the electricity grid is commonly designed for large centralised production units, connected to a high voltage transmission grid that enables transmission of large quantities of power with low losses. High voltages are, however, impractical and dangerous to use close to consumers and the voltage is transformed to lower levels and distributed to the customers through a distribution grid.

The main challenge when operating the power system is to keep the system in balance, i.e. to keep the energy supplied in balance with electricity demand. Different balancing challenges appear on different timescales as shown in Figure 9.1. On short time scales (milliseconds to minutes), the challenges relate to power quality issues, such as stability of voltage and frequency. On medium time scales (minutes to hours), the scheduled production must meet the planned demand and the electricity produced needs to reach the load. On longer time scales (weeks to seasons), the production and transmission capacity should be able meet demand in all parts of the system over the whole year, otherwise loads must be curtailed in order to keep the system in balance.

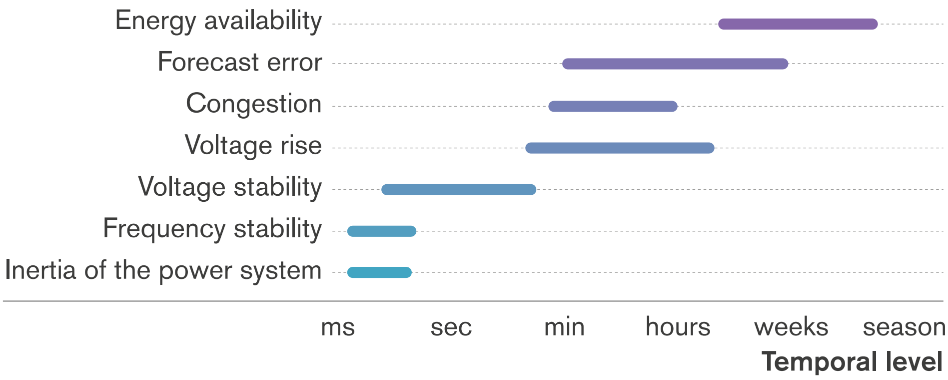


Figure 9.1 Examples of grid related challenges on different timescales.

The challenges also vary between different levels of the power system, e.g. between the local and national level. Small-scale electricity production, such as solar photovoltaic (PV), is usually connected to the low voltage distribution grid while wind turbines are connected to the medium voltage distribution grid or regional transmission grid.

When connecting new generation to the electricity grid, the grid needs to adapt to the new generation. This is valid both for traditional thermal generation units and for renewable sources, such as wind and solar. For traditional large-scale generation sites usually the grid is reinforced to cope with the new generation while small-scale generation to a large extent is integrated into the current electricity grid.

As discussed in Chapter 5, there are several advantages of connecting the generation close to the end user, e.g. reduced losses. However, since electricity produced from solar and wind varies over the day, other challenges arise, both technical and economic. Additional challenges arise from the fact that the localisation of generation units are limited to certain areas, i.e. wind turbines are usually placed in windy areas and not where it is most suitable for the electricity grid, resulting in need for new transmission lines.[1]

There are no major technical limitations on the amount of wind and solar power that could be connected to the grid. However, there might be challenges that need to be considered depending on the characteristics of the energy source and the local conditions at the site where it is connected. At most sites, integration of small shares of wind and solar power require little adaptation of the electricity grid. As the shares increase, the need for adaptation increases and the integration costs may rise.

Rather than trying to provide an exact number of the maximum amount of renewable electricity generation that could be integrated, this chapter aims at highlighting the possible technical and economic challenges that may arise from integration of wind and solar power and how these challenges could be met.

1 For example, this has created large problems in China over the last years, with extensive curtailment, since the grid has not been able to transmit enough electricity from windy areas to demand centres.

Following sections will discuss the challenges related to integration of renewable energy production from different geographical perspectives. In the final section, integration of renewables is discussed from market and policy perspectives.

DISTRIBUTION SYSTEM

In distribution systems the most prominent challenges relates to voltage rise and overloading of system components.[2] While also other issues may arise from fluctuation in electricity production due to gusty winds or cloud movements, this section focuses on these two challenges.

Voltage rise issues emerge when the electricity generated exceeds the local demand, causing the electricity to flow in opposite direction compared to normal operation. This reversed power flow may also affect the protection system and cause overload in system components. There are different approaches to address these problems, e.g. reinforcement in the distribution grid, demand side management (DSM, see Chapter 10), energy storage (see Chapter 5 and 12), energy curtailment, reactive power compensation and coordinated on-load tap changer (OLTC) control. Below, we present the results of case studies on the impact of increasing wind and solar PV penetration levels in two Swedish residential distribution systems.

Both wind power and solar PV will affect the distribution system in similar ways; however there are some major differences. Firstly, the time variation of production differs and secondly the location where they are installed may vary. It is likely that a large share of the solar PV units will be connected to the low voltage distribution system due to its modular properties, allowing for integration in buildings and economic performance independent of scale. In Germany, about 70 % of the solar PV is connected to the low voltage distribution system.[3] Although there are small scale wind turbines that, like solar PV, could be installed within the low voltage distribution system, wind turbines are more likely to be connected to the regional transmission system or to the medium voltage distribution system.

The amount of wind and solar PV that can be installed in a distribution system without violating the reliability and performance of the system depends on the design of the distribution system and on the load profile. Systems with a high mismatch between the electricity generation and demand will have more difficulties to cope with large penetration levels while systems with better load matching can facilitate larger shares. Similarly, systems designed for high peak demand can facilitate more PV and wind power than systems designed for a low peak demand since the system is designed to cope with higher power levels. Other concerns relate to the length of the distribution grid where long distances between the customer and the substation will likely experience increased voltage fluctuations and voltage rises during the day compared to a grid with shorter distances.

Electricity generated from solar PV is rather predictable and, on an aggregated level, it correlates with the demand on a daily basis. For countries with warm

2 Katiraei, F. and Agüero, J. R. (2011), "Solar PV integration challenges", *Power and Energy Magazine*, IEEE , 9(3), pp. 62-71.
3 Appen, J. V. et. al. (2013), Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid", *Power and Energy Magazine,* IEEE, 11(2), pp. 55-64.

weather, it also correlates on a seasonal basis, while for countries with cold climate, like Sweden, there is a negative correlation. On a local level the correlation depends on the characteristics of the area. For commercial areas with peak demand during daytime the correlation is high while for residential areas the correlation is reduced since the demand is highest during morning and evening hours while the peak production occurs around noon.

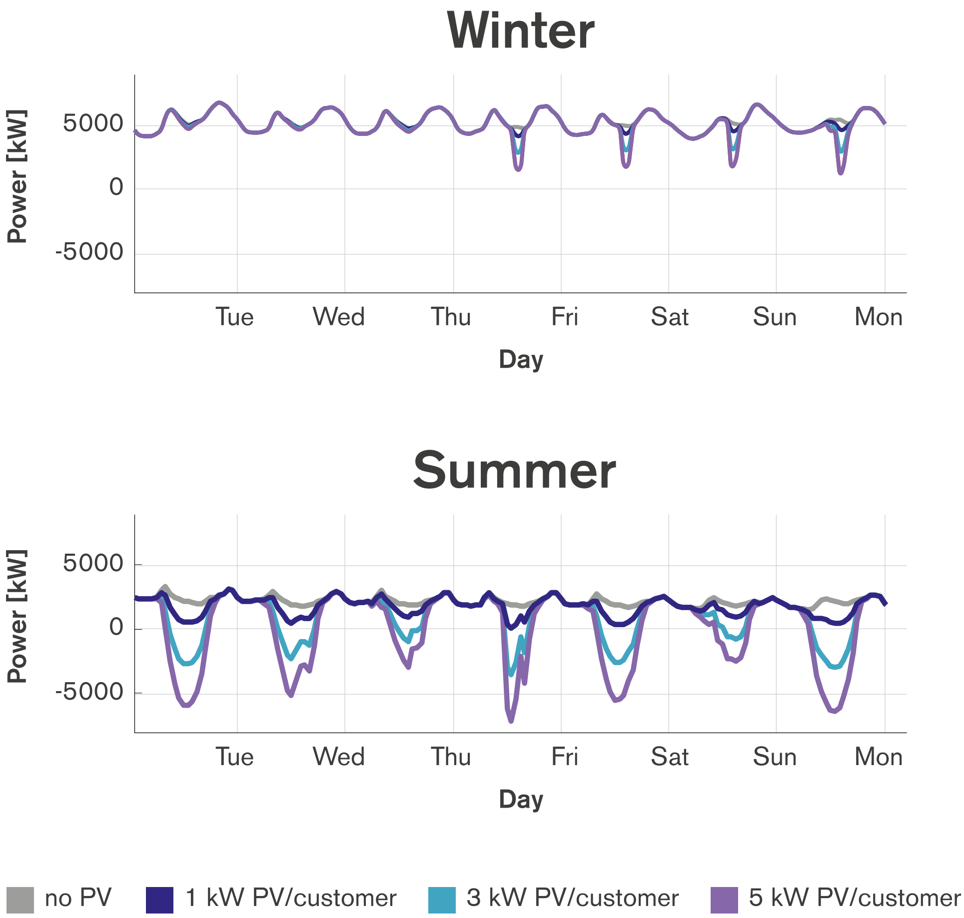
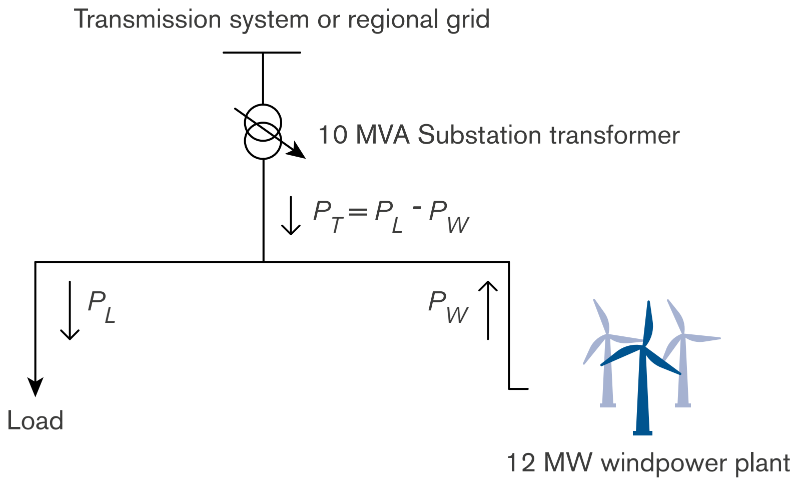


Figure 9.2 Load profile for a residential area in Sweden with different solar PV penetration levels.

To visualise the mismatch, Figure 9.2 presents the net power flow, i.e. the demand minus the generation, in a residential distribution system during a winter and a summer week for different levels of solar PV penetration. As can be seen, all electricity produced by the solar PV is consumed within the distribution system during winter times whereas the reversed power flow is substantial during summer time.

The electricity produced by wind turbines is usually less predictable on a daily basis. This stochastic behaviour can be seen in Figure 9.3, which presents the power output over a year from 13 wind turbines installed in a distribution system in the western part of Sweden, together with the load demand and net power flow. For countries with high electricity demand in winter, e.g. Sweden, there is a seasonal correlation between electricity generation from wind turbines and demand.

(a)



(b)

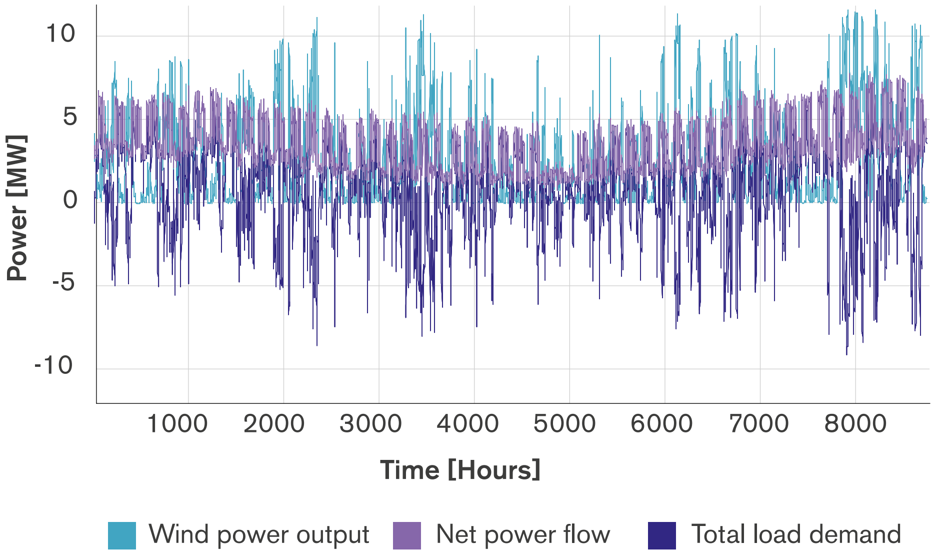


Figure 9.3 (a) A simplified representation of a rural distribution system at the western part of Sweden (b) The total load (PL), wind power in the system (PW), and the total (net) power flow (PT) measured at the substation.[4]

In a PhD project at Chalmers a real residential distribution system in Gothenburg was simulated to assess the technical limit of PV installations.[5] The result shows that PV can supply more than 30% of the annual demand without causing voltage rise or overloading issues. The maximum PV capacity was limited by the conditions on a summer day with low load and high solar insolation, resulting in high reversed power flow, i.e. power flows from the customer to the upstream grid. The limiting factor was a transformer in the medium voltage distribution grid, whereas the low voltage distribution grid could cope with much higher penetration levels. However, since there is a large diversity in how distribution grids are designed these results should be interpreted with care. The maximal penetration level will vary between distribution systems and countries.[6]

4 Negative values here indicate that the power flow is in opposite direction to what is indicated by the arrow (usually expressed as reverse power flow)

5 The model developed includes power flow calculations to set the voltage and current levels within the distribution grid.

6 Other aspects that will affect the result are how the PV capacity is distributed within the system, how the reversed power flow would affect the system at higher voltage levels and short term stability issues.

Traditionally, the connection of solar PV and wind power at a given location in a distribution system is allowed after making sure that the installation does not cause overvoltage or overloading problem when it is producing at maximum power output and when the load in the system is at its minimum. However, due to the rare occurrence of minimum load and maximum power production, shown in Figure 9.3, this approach does not result in the efficient use of the system resources.

As can be seen in Figure 9.3, the power output from the wind farm is rarely above 10 MW and is never above 12 MW. Moreover the minimum system load observed is 0.5 MW, though the maximum wind power output can be as high as 12 MW, the maximum reverse power flow, noticed is 9 MW. This shows that, although the stochastic nature of electricity produced by wind turbines, the coincidence of maximum wind power output and minimum demand is rare. That is, the transformer is less likely to be overloaded due to reverse power flow. Hence, the distribution system can in reality withstand substantially higher penetration levels compared to only considering the maximum power output and minimum loading condition.

To allow further increase in penetration level of solar PV and wind power without reinforcing the distribution system active management strategies, such as, demand side management (DSM), energy curtailment, reactive power compensation, or coordinated on-load tap changer (OLTC), could be used. The principle of DSM is to schedule part of the demand such that overloading and voltage rise is avoided (Chapter 10) whereas energy curtailment avoids the problem by curtailing part of the wind or solar energy. Reactive power compensation and coordinated OLTC control is used in order to bring down the voltage in the distribution system, either by increasing the reactive power consumption by the wind turbines and PV inverters or by a voltage regulation mechanism at the substation transformer. However, this should be done with care, as it may lead to under-voltage in other feeders where wind turbines or PV are not installed.

A case study shows that by applying active management strategies, involving wind energy curtailment and coordinated OLTC control, the hosting capacity of the distribution system can be increased by as much as 83%, compared to the hosting capacity of the network without any active management strategies, with mere 3.3% energy curtailment. The reason for the low energy curtailment needed is due to the rare occurrence of high wind power production and low demand. This level of wind energy curtailment is also seen to be attractive compared to the traditional solution of grid reinforcement within the framework of the study. Similar to the PV study, this study does not consider impact on the upstream grid or short term voltage stability.[7]

TRANSMISSION SYSTEM

What is usually referred to as the transmission system for electricity is the high voltage backbone of the electricity grid. The need for a transmission grid, i.e. the need to transport electricity over long distances, stems from the fact that generating units are not necessarily (and usually not) located close to the load. From a transmission point of view, the ideal placement of generators would be as close

7 Salih, S. N. et al. (2014), Optimizing wind power hosting capacity of a distribution system using costs benefit analysis, IEEE Transactions on Power delivery, submitted for publication.

to the load as possible, but the locations of power plants are determined by a number of factors. For example, it can be economically beneficial to concentrate production to large facilities supplying a large geographical area, because of economies of scale. Other circumstances such as proximity to harbours and other infrastructure, or availability of certain natural resources such as coal mines, rivers or sea water used for cooling in thermal power plants, may also influence where a plant is built.

In general, large-scale integration of solar and wind power can cause three major changes in the way the transmission system is utilised. First, the optimal locations of power plants may change, since the optimal sites for wind and solar power plants are often not the sites where power plants have traditionally been placed. Second, increasing the transmission capacity can be used for smoothing variations in the production patterns from wind and solar power. This is possible since the correlation between wind and solar patterns generally decreases with geographical distance. With a large transmission capacity, electricity can be collected from a large geographical area, resulting in smaller variations in aggregated production.[8] Third, an expansion of transmission capacity may be needed to better utilise resources, such as hydropower, that are capable of managing supply and demand imbalances in the system.

As previously discussed, one of the main challenges with operating the power system is to keep the demand and supply in balance to avoid frequency deviations. Traditionally, flexible generation units have been used to reduce or increase the production to keep the power balance. As the amount of intermittent electricity generation increases the need for balance power may increase at the same time as old flexible generation units are being replaced by renewable generation units.

In this new situation curtailing can be used if generation needs to be reduced (down-regulation). Increasing the production (up-regulation) from the intermittent energy sources is more difficult since they cannot increase their production if they already utilise all available energy. Instead other measures, such as DSM and energy storage could be applied. These techniques are further discussed in e.g. Chapter 5, 10 and 12. There is also ongoing research, investigating the possibility to use the inertia of wind turbines to provide frequency support by controlling the turbines in a novel way.[9]

Decommissioning of existing power plants may cause other challenges within the power system. As one example, nuclear power plants in Sweden are not only providing active power to the customer but also reactive power. Reactive power is consumed both by customer equipment, e.g. electrical machines, and by the power system itself, e.g. due to inductance in overhead lines. By reducing the reactive power injection in one part of the system, the reactive power consumed must be transferred from other parts of the system. This in turn will limit the ability to transfer active power in the system since the current, which limits the transmission capacity, is affected by both the active and reactive power. However, wind

8 Reichenberg, L. et al (2014), "Dampening variations in wind power generation - the effect of optimizing geographic location of generating sites," Wind Energy, in press.

9 Persson, M. et al. (2013), Frequency Support by Wind Farms in Islanded Power Systems with High Wind Power Penetration, IEEE PowerTech2013 Conference, June.

turbines and solar PV have the ability to provide reactive power, and in many countries it is required for new plants.[10]

Limitations in the transmission grid may hinder an economically efficient operation of the system, e.g. by hindering the most desirable generation units from satisfying the demand.[11] This is commonly referred to as congestion in the electricity grid. The grid is congested if the system would benefit from transferring more power from a generator at point A to a load at point B, while that is not possible because of the limited capacity of a transmission line, safety limits, or other constraints. In the presence of congestion, the demand at point B can still be met (otherwise there would be a blackout), but less desirable generating units will have to be used.

When there is congestion in the grid, the marginal cost of electricity, i.e. the increase in costs to satisfy an additional unit of demand, will vary between locations. The marginal cost difference is an indicator of congestion. If the cost of generating an additional unit of electricity is lower at point A than at point B, it would be preferable from the system's perspective to reduce the production of the most expensive generator at point B and instead buy electricity from point A. Therefore, if the trade between A and B is not limited, i.e. there is no congestion, the marginal costs at A and B will be equal, because an additional unit of demand at either of the points can be satisfied by the same generator. A difference in marginal cost will only persist if there is some constraint on the trade between A and B. The total generation cost in the system will therefore also be higher in the presence of congestion. However, there is a trade-off between the additional generation costs incurred by congestion and the costs of increasing the transfer capacity of the grid. Therefore, there may still be congestion when the total costs, including costs for generation and grids, are minimised.

Expanding electricity production from solar and wind in Europe will most likely impact the congestion patterns in the transmission grid. As solar and wind provide electricity with low marginal cost of production, they will lower the electricity price in the area where such generation occurs. This will result in demand for this low cost power from other parts of the system.

The congestion patterns can be studied using computer models of the European generation and transmission system.[12] Typically, such models determine how the power plants in each region should be run to minimise total system costs. Congestion is revealed by remaining regional differences in electricity prices.

10 Singh, B. and Singh, S.N. (2009), Wind Power Interconnection into the Power System: A Review of Grid Code Requirements, *The Electricity Journal*, 22(5), pp. 24-63.

11 When the goal is a system with lowest possible cost, as is most often the case with the electricity supply system, the generation cost usually determines which units are the most desirable.

12 Göransson, L. et al (2013), On the relation between Demand Side Management and congestion in the European electricity transmission system, submitted for publication.

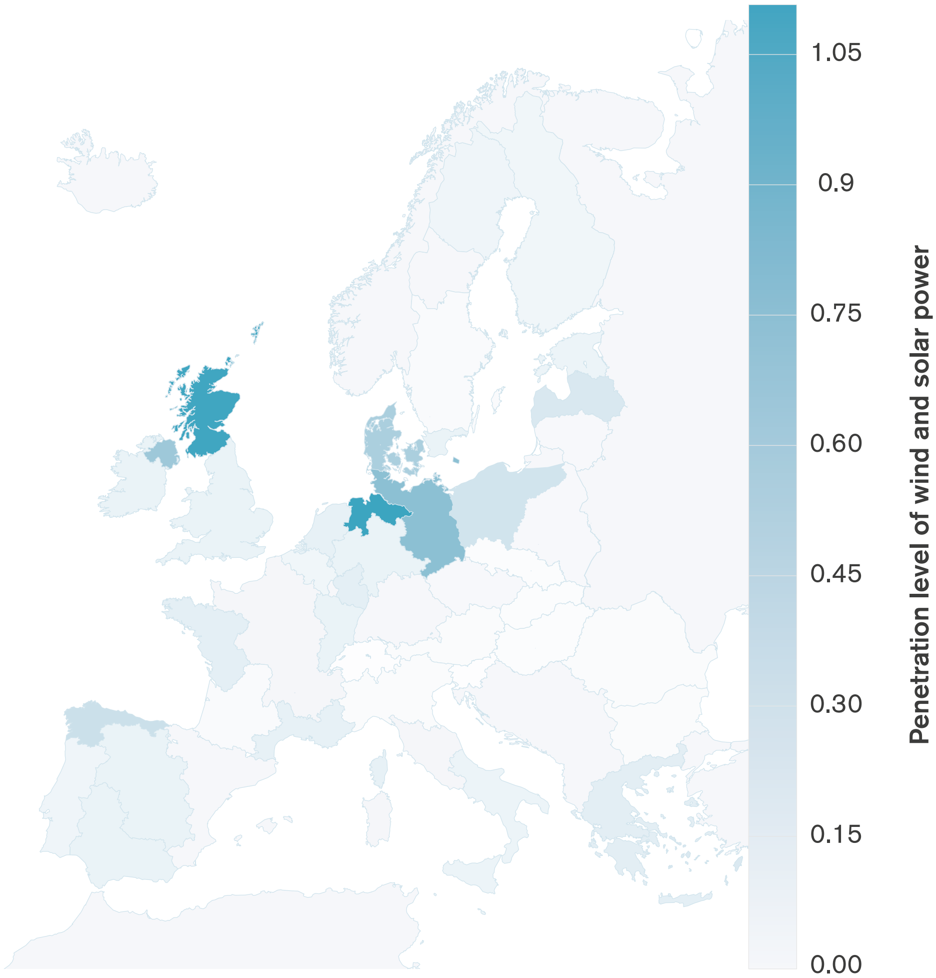


Figure 9.4 The energy penetration level of wind and solar power in a scenario for the European electricity system in 2020. The penetration level is calculated as the total electricity production from wind and solar power in one year in each of the 50 regions shown on the map, divided by the total consumption of electricity in that region during the same time period.

Figure 9.4 shows the penetration levels of wind and solar power in the European electricity system in 2020 given a scenario of rapid expansion. Europe is here subdivided into 50 regions. The penetration level is calculated as the total electricity production from wind and solar power in each region in one year, divided by the total consumption of electricity in that region during the same time period.

In such a scenario, congestion in the transmission system is strongly affected by the production of wind and solar power. To illustrate the effects, Figure 9.5 and Figure 9.6 show marginal generation costs in Europe in two different situations. In Figure 9.5, wind power production is high, while load (demand) is relatively low. This results in very low marginal costs in the regions in northern Germany, while neighbouring regions to the east and south have much higher marginal costs. This indicates that the cheap wind power cannot be transmitted to these regions because of limitations in the grid.

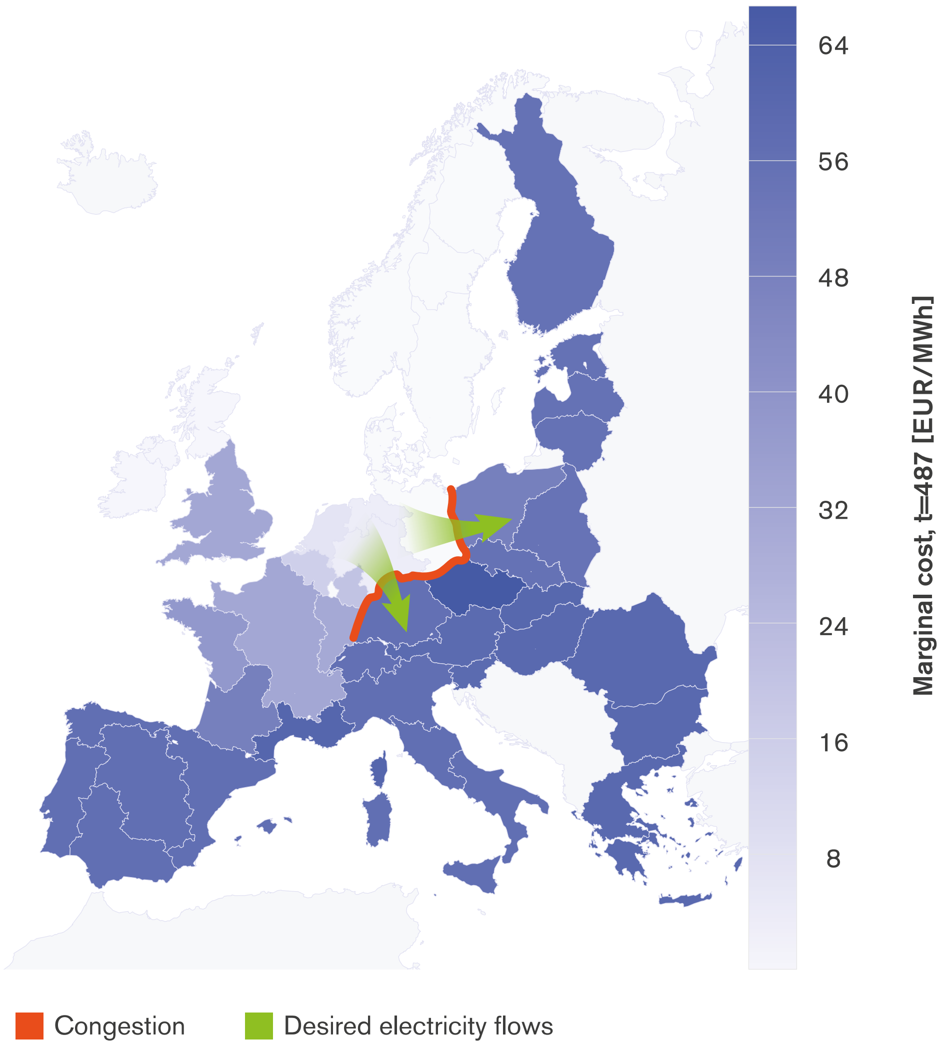


Figure 9.5 An example of marginal generation costs in the 50 regions in one time step in the simulated European electricity system, where the wind power output is high in northern Germany. This situation causes congestion, which can be seen through the differences in marginal costs between the brighter coloured regions in northern Germany, and the darker coloured regions in the south-eastern parts of Europe. The congestion is illustrated by the yellow curve in the figure and is an example of a congestion pattern strongly affected by wind power production.

Figure 9.6 shows a completely different situation, where marginal costs are very high in the central parts of Europe, due to high load, and lower in the Iberian Peninsula, southern Italy, and Scandinavia. Congestion arises, since the transmission system does not allow for the cheap solar power in southern Europe and the cheap hydropower in northern Europe to be sufficiently distributed to the central regions.

The examples explained above demonstrate that extensive deployment of wind and solar power may have a large impact on congestion in the European transmission system. The new congestion situations that arise with large amounts of wind and solar power in the system do so due to the fact that the present transmission system was not designed with these conditions in mind. Therefore, the planning of the future transmission expansion will have to be made taking into account the locations and properties of the variable renewable resources that will become increasingly important in the future.

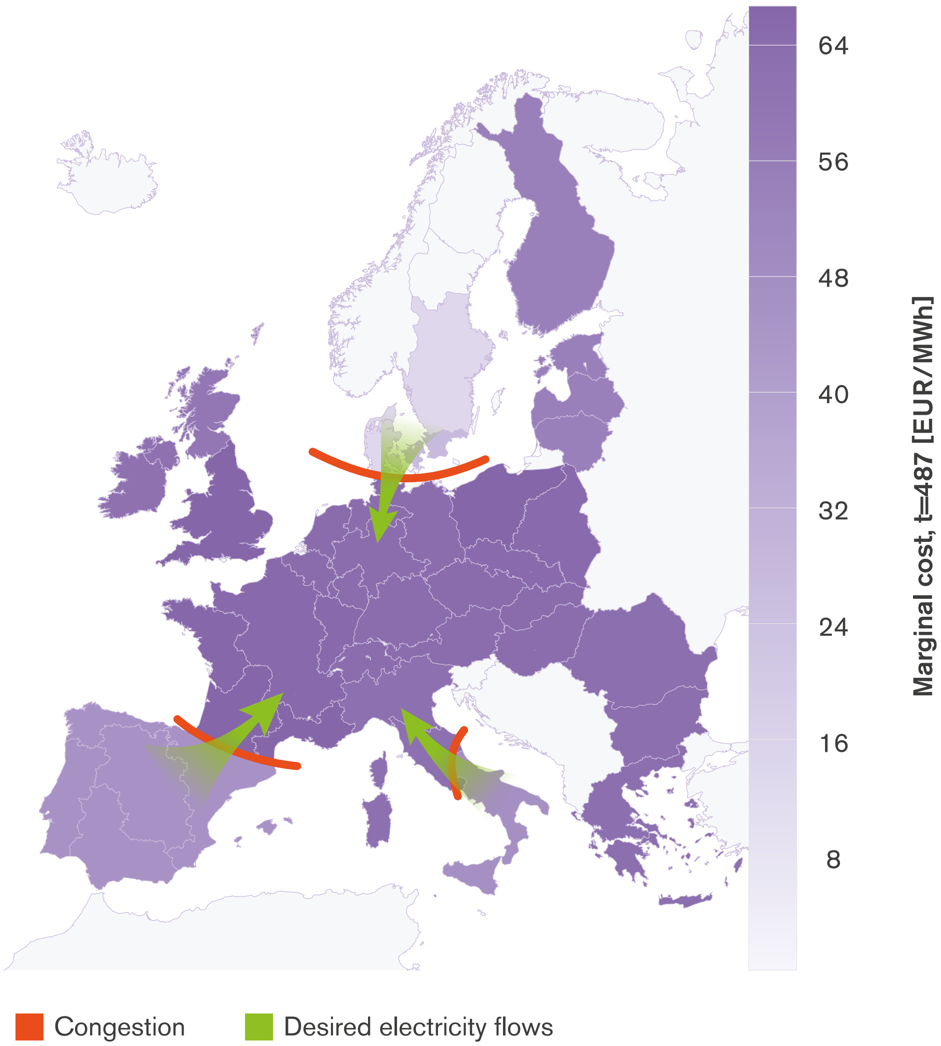


Figure 9.6 An example of the marginal generation costs in the 50 regions in one time step in the simulated European electricity system, where load is high in the entire system and where solar power production is high in southern Italy and in the Iberian Peninsula. In this case congestion arises between the central parts of Europe where marginal costs are high due to the high load and the southern parts where cheap solar power is available. There is also congestion between Scandinavia, where there is cheap hydropower, and continental Europe. The congestion is illustrated by the yellow curves in the figure.

This will give the opportunity to lower the electricity prices as well as increase the value of the electricity produced by new power plants by investments in the grid. These investments will be economically profitable and small compared to the investments in the new power plants.

MARKET DESIGN AND POLICY IMPLICATIONS

This section briefly discusses some market design issues and possible solutions related to challenges arising from large-scale integration of wind and solar power. The role of the market is to facilitate an efficient operation of the power system, but also to provide long-term incentives for investments in e.g. transmission and production capacity. Even though the physical laws of electricity are the same all over the world, market organisation and policy concerning electricity trade differ significantly between regions. Here, we mainly apply a European perspective on the power market.

One major factor concerning investments in wind and solar power is the actors' expectations concerning market prices and possible revenues. An important question related to pricing is the method to handle congestion in the transmission system, since this will heavily affect the resulting market prices in different parts of the system. Area pricing is one such method commonly applied in Europe, and which also is used in the Nordic countries. The method implies that there are different prices in different parts of the system. One of the reasons for the introduction of such price areas is to provide incentives to locate new production, such as wind and solar power plants, closer to load centres.

In order to promote investments in renewable energy, different economical instruments can be introduced. One example is feed-in tariffs, where producers of renewable energy are guaranteed a certain price for the energy they deliver to the grid. This is applied in for example Germany. Another example is green certificates, which was introduced in Sweden in 2003. Production resources being classified as renewable then also produce a financial instrument, a green certificate, for each MWh of production. The consumers are mandated to buy green certificates representing a specified share of their electricity consumption. The green certificates are traded on a market and the owners of renewable power plants get revenues also for the green certificates. Thereby they get an increased economic incentive to invest in renewable energy production.[13]

Concerning market design and incentives for investments in wind and solar power, the balance settlement process and the possibility to adjust traded volumes according to updated production forecasts are important issues. The most common way of trading electricity is through a day-ahead spot market,[14] which means that production forecast for 12-36 hours are required in the trading process. This is of course a great challenge for wind and solar power owners. In the imbalance settlement, performed after the actual hour has occurred, the deviation between traded volumes and actual volumes for that hour is managed economically. Such deviations can induce significant imbalance costs for owners of intermittent wind and solar power producers due to forecast errors. One way of managing this is to act on the adjustment market,[15] where the traded volumes on the spot market can be adjusted according to forecast updates. This is a market place which is foreseen to play a more central role in systems with large amounts of wind and solar power, and which facilitates risk mitigation for owners of such power plants.

As the amounts of production capacity increases in the system, the units having the highest marginal costs will be used less hours during the year. This means that at some point the generating companies will take these units out of operation since they will not any longer carry their own costs (Chapter 11). However, even though the plant owners interests in keeping generation capacity would decrease there could still be a need to keep capacity in the system in order to maintain the reliability of the power system, e.g. in situations with low wind power production and high loads.

13 Factors that limit the impact on investments in renewable power of the green certificate scheme are discussed in Chapter 15, and some aspects of the political context of the German and Swedish systems are discussed in Chapters 13-14.

14 Day-ahead spot markets exist all over Europe. In the Nordic case, the spot market is owned and operated by Nord Pool.

15 In the Nordic system, the adjustment market is called Elbas and is operated by Nord Pool.

One way of creating incentives to keep capacity is to introduce capacity markets or capacity credits,[16] where producers (and possibly consumers) can get economic compensation for keeping generation capacity. The owners of production resources on the capacity market are free to use their capacity for generation and trading on the energy market. The point of capacity markets it to encourage retention of existing resources, as well as for investing in new generation, so these can be used on the market providing electricity when needed.[17]

Investment in transmission capacity is a question of great importance in order to benefit from renewable power sources being localised in different parts in the system. Transmission network expansion is a responsibility of the transmission system operator (TSO), which in many systems and countries is a public utility. The economic incentive to increase transmission capacity depends on several factors: one is the owner directives, in which the owner (i.e. the government) states targets for the TSO and relate this to economic instruments; another is the choice of congestion management scheme defining how bottlenecks in the transmission should be handled financially. As previously stated, area pricing is commonly applied in Europe. One drawback of area pricing is that the TSO benefits from price differences[18], resulting in a lack of incentive to invest in transmission. This can however be handled by strong owner directives creating sufficient economic incentives by relating to the number of congested hours or similar.

The distribution networks are in many systems operated by companies having monopoly of the distribution of electricity in a certain geographical area. In order to make sure these actors don't abuse their monopolistic position, they are regulated and monitored by the authorities. The regulation design defines the economic incentives for the distribution system operators (DSOs) to invest in the grid, and also imposes restrictions on the DSOs operation of their grid. In terms of integration of wind and solar power in the distribution grid, it is important that the regulation allows investments facilitating an efficient operation of the network in areas with large amounts of distributed production. The possibility for DSOs to use energy storage in the distribution network is one such issue that needs to be addressed.

The unforeseen production variations of wind and solar power will increase the need for balancing power and frequency control measures. Frequency control is usually performed in several steps: primary, secondary and tertiary control. The two first are usually performed by technical systems installed at certain production units, reacting automatically to deviations from the nominal frequency level. The tertiary control is often market based, where the TSO can trade power in order to release capacity for primary and secondary control. Such markets are sometimes referred to as real-time balancing markets.

16 Brunekreeft, G. et al. (2011), *A Raw Model for a North European Capacity Market - A Discussion Paper*. Elforsk rapport 11:30.

17 See also Chapters 2 and 13 for a discussion on capacity markets and similar arrangements as a way for incumbent utilities to protect the value of their assets.

18 The economic transaction related to transmission consists of the TSO trading electricity between the connected areas. Electricity is bought in the exporting area and is sold in the importing area. Congestion implies different prices in the different areas, where the exporting area will have a lower price than the importing area. The resulting trade thereby results in revenue for the TSO which can be calculated as the price difference multiplied with the transmitted electricity.

In the Nordic case, the main resource for balancing the power system is the hydropower system which is very flexible in terms of changing the generation level. However, most parts of Europe lack such flexible production resources. When introducing large amounts wind and solar power, it might also be efficient to further explore the possibilities to use the load as a balancing resource (DSM is further discussed in Chapter 10). In some systems, large industrial consumers already act to some extent on the real-time balancing market providing tertiary control capacity. However, it can also be efficient to use more distributed resources consisting of for example household heating systems through aggregators to provide system services. This might require new market designs allowing and facilitating these kinds of market actors to be a part of the frequency control.

CONCLUDING REMARKS

In this chapter different aspects and challenges related to integration of electricity production from wind and solar in existing electricity grids have been discussed. The main challenge with integrating wind and solar is due to the fluctuations in the power generated from these sources. From a technical point of view there are no major limitations to the amount of wind and solar that could be integrated into the power system. However, it results in new conditions that the electricity grid needs to be adapted to.

Integrating wind and solar production in a distribution system could cause voltage rise and overloading of system components. On the other hand it could also reduce losses within the system. For the transmission grid, the challenges can be visualised as congestion between areas. Although there is congestion between areas already today, the congestion patterns change with increased wind and solar production. This shows that the demand for new transmission capacity between areas may also change with increased electricity production from wind and solar. Other alternatives, such as storage (Chapter 5), production of electrofuels (Chapter 12), and demand side management including demand response (Chapter 10) could be used to reduce the demand for transmission capacity.

Market will play an important role, both to create incentives for investments in renewable generation technologies but also to maintain the balance between demand and supply of electricity over different time scales and to ensure investments in transmission and distribution capacity. As a consequence, increased wind and solar power production will require new institutional arrangements.[19]

19 The importance of institutional arrangements is further discussed in Chapters 2 and 13-16.

10

CAN DEMAND RESPONSE MITIGATE THE IMPACT OF INTERMITTENT SUPPLY?

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INTRODUCTION

Traditional electricity systems have been designed to have the production side respond to changes on the demand side. The production has consisted of base load plants, generating electricity at a fixed level, and flexible power plants following demand fluctuations. However, increased electricity demand creates a need for more production and grid capacity. To avoid or defer such investments, it is possible to instead give customers incentives to reduce their demand during peak load hours. This concept is often called demand response (DR). DR, which deals with manipulating the demand curve, is part of a broader concept called demand side management (DSM) which encompasses all measures implemented on the demand side of the energy system.

As shown in Chapter 9 the introduction of renewable power could lead to new challenges for the electric grid, e.g. congestion and frequency instability. The need for flexible production or consumption may thus increase. Hence the importance of demand response may increase with increased production of intermittent renewable power. In Figure 10.1, the issues that can be addressed are encircled, it can be seen that demand response can help alleviate problems both on short timescales (milliseconds to minutes) and medium timescales (hours to days).

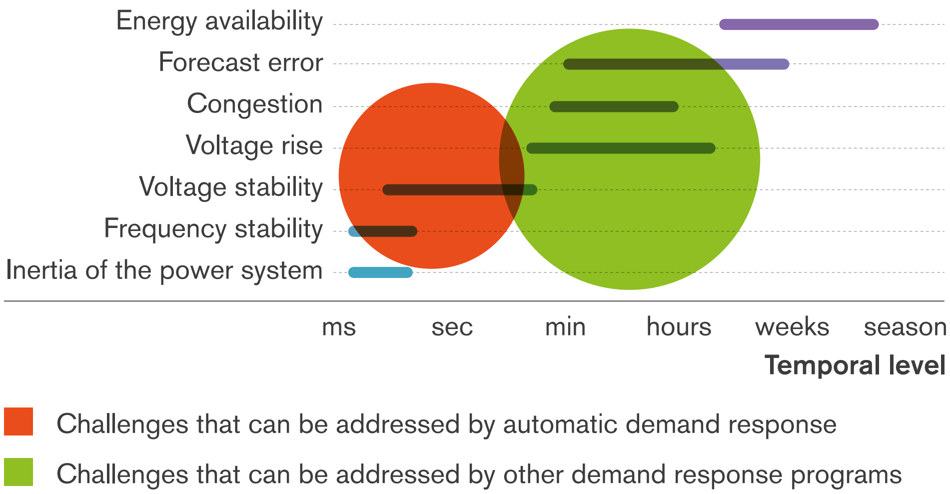

Figure 10.1 Grid related challenges where demand response could be effective; the red circle represents the challenges that can be addressed by automatic demand response; the green circle represent challenges that can be addressed by other demand response programs.

In this chapter some of these solutions are addressed together with a short summary of what demand response entails for different demand sectors. Two case studies are presented investigating how demand response could support integration of intermittent renewables to increase the maximum penetration level in the distribution system and to reduce congestions in the transmission system.

WHAT IS DEMAND RESPONSE?

Electricity demand is to a large degree seen as uncontrollable from a producer's point of view and varies with time of day and season, and consists of a large number of individual loads, from home appliances to industrial equipment. Conventionally, these loads and any changes in them are met by varying electricity generation up or down. However, some loads are not immediately required and could be shifted in time. Demand response implies that loads are dispatched or reduced to balance demand and supply. This dispatch occurs through implementing incentives or restrictions for the electricity consumer who is in control of the load. Demand response is thus a change made in the consumption pattern of an electricity consumer instigated by some driving force.[1] This change can be load curtailment, i.e. reducing the load, or a load shift, i.e. shifting the load in time. Thus, demand response can both result in a reduction of demand as well as a shift of demand in time. A reduction should not be equated with efficiency improvements as the reduction is due to a removal of load and not an improvement of its efficiency.

Traditionally, demand response has meant that the demand should be "flattened" to as large degree as possible.[2] The rationale for this is that less variation in demand reduces the need for reinforcements of weak grids (see Chapter 9),

1 Palensky, P and Dietrich, D. (2011), Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads, IEEE Transactions on Industrial Informatics, 7(3), pp. 381-388.
2 See for example Doudna, J.H. (2001), Overview of California ISO summer 2000 demand response programs, Power Engineering Society Winter Meeting, IEEE, 1, pp. 228-233.
and Albadi, M.H. and El-Saadany, E.F. (2008), A summary of demand response in electricity markets, Electric Power Systems Research, 78(11), pp. 1989-1996.

reduce the losses, reduce investments in new peak power plants and reduce the use of expensive peak power plants, i.e. generation units with high running cost (Chapter 11). However, as more intermittent production is introduced, the goal is no longer to "flatten" the demand but instead make demand follow the intermittent patterns from the renewable production.

Figure 10.2 illustrates the difference in strategy, the left graph being the traditional way of demand response and the right presents demand response in a system with distributed intermittent generation. It can be seen that in the case of distributed intermittent electricity production a shift in demand could lead to increases in peak demand compared to the traditional case where the goal always is a reduction in peak demand. It should be noted that for distributed intermittent generation the increased peak demand may not affect the upstream grid since the electricity is produced locally while for systems with large centralised intermittent generation, e.g. large offshore wind power parks, the possible load shift may be limited by the transmission capacity of the grid.

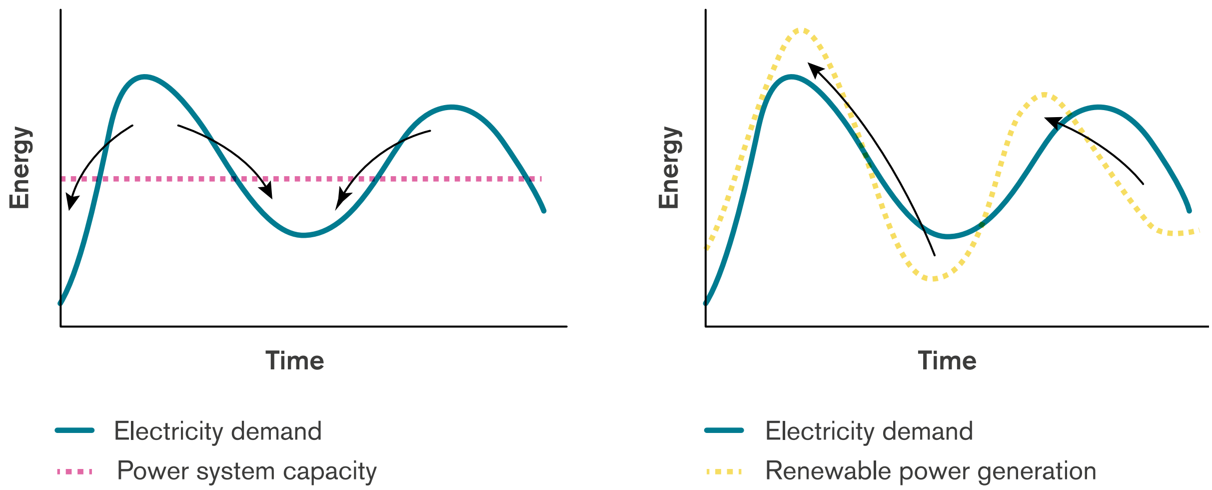

Figure 10.2 The difference between demand response strategy in a traditional electricity system (the left) and one with a considerable amount of intermittent generation (the right).

DEMAND RESPONSE IN DIFFERENT DEMAND SECTORS

Controllable loads are available in all sectors on the demand side, domestic, commercial and industrial. However, the sizes of the loads, how far in time they can be shifted, how inconvenient it is and the cost associated with shifting vary between different sectors.

For the domestic sector demand response could mean shifting of loads which services are not immediately required, e.g. starting the dishwasher an hour later. Other examples of similar loads are washing machines and dryers. Such loads are used to shift energy and can usually be shifted quite far in time (hours). However, once they have been started it is often inconvenient to stop them. There is also the possibility of using loads that can be shifted for short periods of time (up to minutes) but can be started and stopped without major implications, e.g. freezers and refrigerators. These loads can then be used for frequency control (see Figure 10.1). Electric space heating, water heating and air conditioning could also be used through storing hot water or allowing the indoor temperature to vary within a given temperature range. The size of space heating and cooling loads and the timeframe over which they can be shifted depend on building material and isolation as well as weather conditions. Available loads in Swedish households are provided in Table 10.1. The largest potential lies in shifting the heating demand. In warmer regions air conditioning is instead the major load.

All of these measures cause no or little inconvenience for the end user as the service of the appliance is still provided. However, there are limits to how far in time these loads can be shifted. These limits are set by the preferences of the consumers, i.e. the acceptable temperature range and acceptable time a load can be postponed or advanced. There is also the possibility for the consumer to avoid using a load altogether. However, this would imply that the service is not provided thus possibly reducing the comfort of the user.

Table 10.1 Important characteristics and corresponding average values for different DR loads in Swedish households with a distinction between single family dwellings (SFD) and multi-family dwellings (MFD).[1,2]

Load	Household type	Load size (Energy demand) (kWh/year)	(kWh/cycle)	Cycle time (hours)	Displacement time (hours)	Prevalence (appliance per household)
Space heating[1]	SFD	6800-20000	n.a	n.a	n.a	n.a
	MFD	n.a				
Water heating[1]	SFD	1500-3000	n.a	n.a	n.a[2]	n.a
	MFD	n.a				
Fridge	SFD	200-230	n.a	n.a	0-1	0.62
	MFD	140-260				0.32
Fridge-Freezer	SFD	410-530	n.a	n.a	0-1	0.38
	MFD	450-500				0.58
Freeze	SFD	370-590	n.a	n.a	0-1	0.88
	MFD	330-440				0.45
Dishwasher	SFD	140-240	0.2-1	2	0-24	0.9
	MFD	70-210				0.51
Washing machine	SFD	110-210	0.3-1.2	1-2	0-24	1.01
	MFD	60-170				0.52
Dryer	SFD	100-130	0.4-2	1	0-24	0.59
	MFD	240-320				0.15

[1] Includes only direct electric heating. Source: Zimmermann, J. P. (2009)

[2] No values are given for space and water heating loads as these values highly depend on the storage capacity and the acceptance range for temperature fluctuations. Source: Timpe C. (2009)

In the commercial sector, which includes public buildings as well as offices and shopping malls, controllable loads are similar to those in the domestic sector. However, the possibility to shift appliances is limited, since most loads are used continuously, e.g. computers. Air conditioning and heating loads have, as in the domestic sector, the largest potential. There are other loads that could be used as well, for instance ventilation and regulation of the intensity of lighting.

For the industrial sector demand response could mean rescheduling of loads or shedding loads, i.e. stopping production or using duel fuel systems where other fuels can temporarily replace electricity. Industry demand response is already to some extent used today, through industries that take part in the electricity reserve, balancing and frequency markets. Here industries commit to shutting down loads in case the strain on the power system becomes too big. However, there might be possibilities for industries to reduce their costs further through a more active demand response.

Stopping production is associated with a loss in income, and to be attractive, savings from avoided electricity use have to be equal or greater than this loss. This means that electricity intensive industries, i.e. industries where electricity is a major part of production cost, are more likely to engage in demand response. Another limiting factor is the relatively low fluctuations in electricity prices making production planning based on electricity cost a low priority even if there where savings to be made. Rescheduling of loads requires that the load in question is flexible. Loads which operate at maximum capacity, i.e. are operated at all times, obviously cannot shift in time. Similarly, loads that are bounded to certain hours cannot be shifted either. In such cases, load shedding is the only possibility.

DEMAND RESPONSE PROGRAMS

There are several different ways to create incentives for electricity consumers to take part in demand response programs. Demand response programs could be designed in different ways depending on the aim. Figure 10.3 presents some of the DR programs that are in operation today. Most of these programs, e.g. critical peak pricing (CPP), locational marginal price (LMP) and direct load control (DLC), have been introduced to cope with issues related to power system stability and capacity problems in the power system. However, some could also be beneficial to use in systems with a high share of intermittent electricity generation. This section introduces some of the DR program that are employed today and that could be used to balance production from intermittent renewables.

As discussed above, demand response can mainly support renewable energy sources in the short to medium time range. On the short time range, e.g. for frequency stability, automatic demand response programs, such as direct load control (DLC), must likely be used to manage the fast response time needed. On the medium time range, other concept such as, real time pricing (RTP) can be an efficient measure to cope with intermittency in the production on a daily basis.

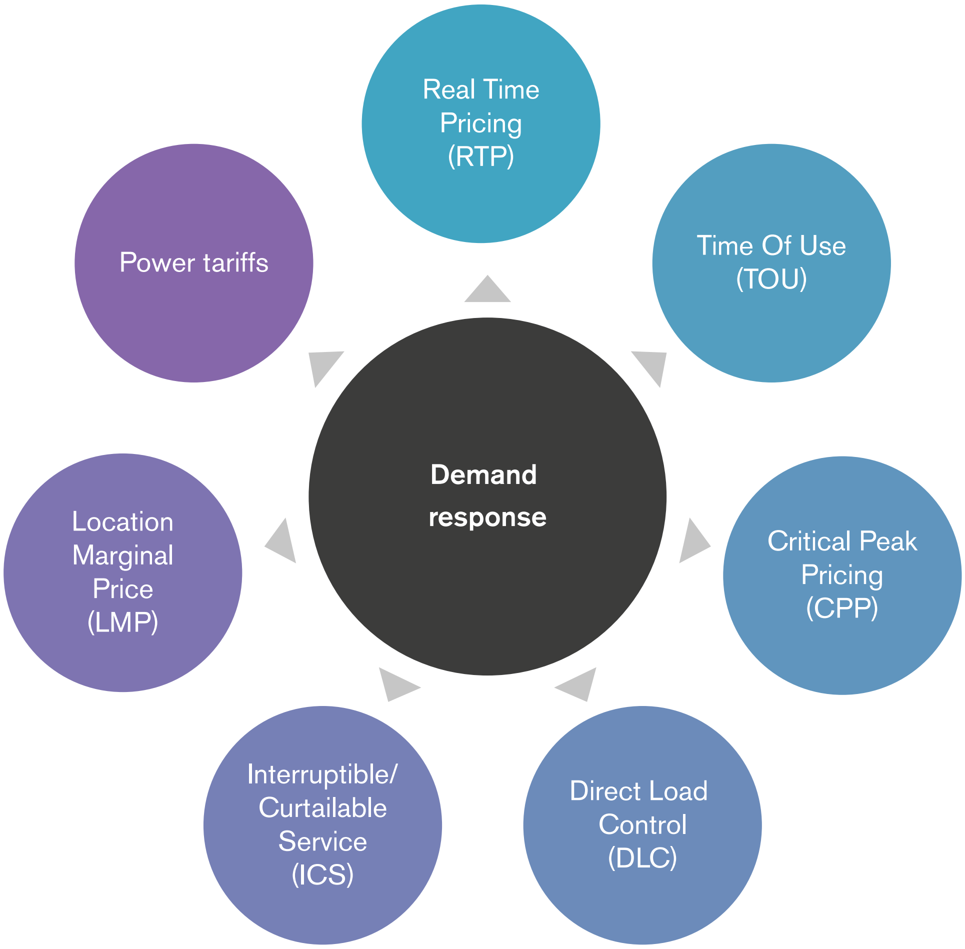

Figure 10.3 Different types of demand response programs.

DLC programs can be implemented both to cope with local congestions in the power system and for frequency control. These programs are most often automatically controlled and the customer appliances receives a signal from the transmission system operator (TSO) or distribution system operator (DSO) to reduce or turn off the power. Other ways are to use frequency measurement that automatically reacts on frequency deviations. Traditionally, customers could sign up for these programs and were then economically compensated for their reduction. However, other business opportunities arises, e.g. TSOs could subsidise thermostatically controlled equipment, such as refrigerators, heat pumps, air conditioners or water boilers equipped with a frequency control unit to give customers incentives to buy them. A study has shown that an aggregation of a large number of dynamically controlled loads has the potential to provide significant added frequency stability to power systems, both at times of sudden increase in demand (or loss of generation) and during times of fluctuating wind power.[3]

As discussed in Chapter 9 and 11, it is likely that the need for regulating power increases with increased levels of intermittent renewable generation. In the Nordic electricity market, the demand side can participate in both the regulating market, e.g. to maintain the balance and frequency within the system, and in the peak load

3 Short et al. (2007), Stabilization of Grid Frequency Through Dynamic Demand Control, IEEE Transactions on Power Systems, 22(3):1284-1293.

reserve, a reserve used to meet the demand when it is critically high. Today the majority of the reserve is provided by the generation side although the Swedish TSO is aiming at increasing the participation of the demand side.[4]

Although it is possible for electricity customers to participate, the requirements regarding response time and regulating capacity is high. These requirements leads to that the participating customer must either have a high demand, which is the case for industries or large commercial buildings, or be aggregated together with other customers. With evolving business models and increased incentives, the demand side participation may play an important role in the future regulating market.

The idea with real time pricing (RTP) is to let customers react on price fluctuations on the electricity markets by reducing or increasing their flexible demand. The electricity price depends both on the demand and the available generation. When there is a surplus of generation or low demand, the electricity prices are generally low while the opposite holds when there is a shortage of generation or high demand. For power systems with a high share of intermittent generation, situations with surplus or deficit will likely be more common and lead to a more volatile electricity price. RTP will create incentives for customers to reduce their demand during peak hours and increase it during off-peak hours, or during hours with excessive renewable production. This would both increase the power system reliability and help integrating intermittent renewable energy sources.

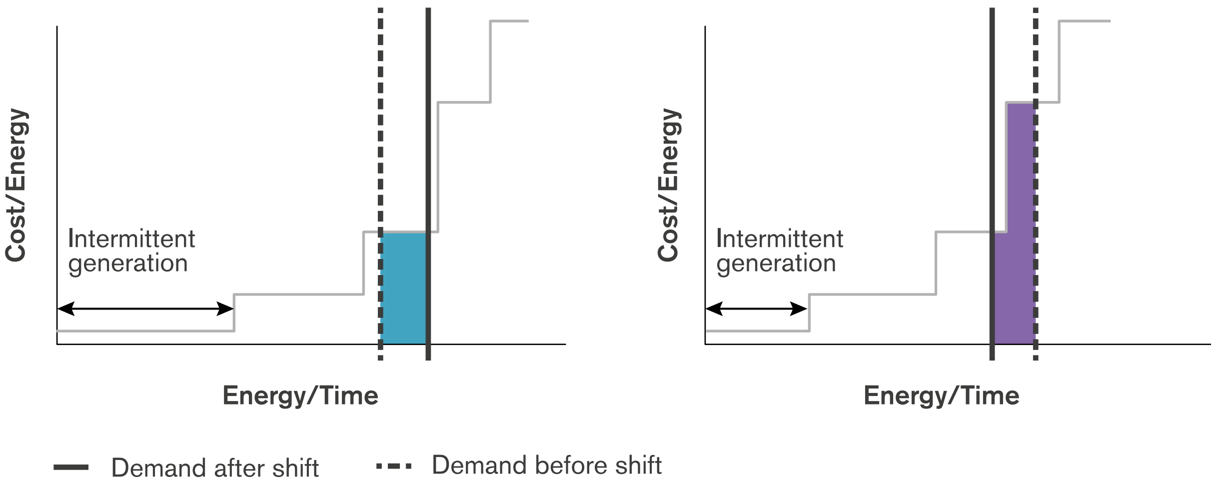

Figure 10.4 Supply curves for two different hours, one with a high amount of intermittent generation (the left) and one with a lower amount of intermittent generation (the right). The coloured areas are the reduction in system cost (purple) and increase in system cost (teal) after a shift of demand from the hour with low intermittent generation to the hour with high intermittent generation.

As an example, one can take two hours with the same amount of load. During one of the hours there is a lot of intermittent renewable electricity generation and in the other there is not. As the generation cost of intermittent renewable electricity is almost zero the marginal cost of production would be different in the two cases, see Figure 10.4. In the low intermittent renewable generation case (to the right in Figure 10.4), the marginal electricity cost is higher. If load could be moved from

4 Svenska Kraftnät's press release "Principer för hantering av effektreserven", March 16, 2011.

the hour with low intermittent renewable generation to the hour with high intermittent renewable generation the total cost of electricity for the two hours could be reduced. The area marked purple is the decrease in system cost for the low intermittent renewable generation hour and the area marked teal is the increase in cost for the high intermittent renewable generation hour. The purple area is larger than the teal resulting in a net reduction in system cost.

One important aspect regarding the design of an RTP scheme is the time difference between the announcement of the price to the customers and the actual consumption. A long time lag, e.g. using day-ahead price, would result in a price that less accurately reflects the demand and supply, which may result in increased need for balancing power. A shorter time lag would result in better reflection of the balance between demand and supply but with more difficulties for the customer to plan their electricity consumption, since they must forecast the electricity price for the coming day. Since the load profile could vary within different parts of a price area there is a risk of increasing the peak demand locally. The risk also increases with longer time lags and higher shares of flexible demand. This could be solved by implementing RTP together with some other demand response program such as power tariffs or locational marginal price.[5]

WHAT CAN DEMAND RESPONSE DO AT THE DISTRIBUTION SYSTEM LEVEL?

As shown in Chapter 9, the amount of intermittent electricity generation that could be integrated into the medium voltage distribution system investigated in the case study without any need for reinforcements of the system was limited to about 30% of annual demand. Reinforcing the system may be costly and other measures can be used to enable higher penetration levels at a lower cost. One of these measures could be to use DR.

A model aiming at investigating how DR can be used to increase the amount of PV that could be integrated into a residential distribution system without any reinforcements is currently under development at Chalmers. The model uses the same distribution system that is presented in Chapter 9. Up to now, only heat loads, e.g. space heating, are considered to be flexible although other loads, such as laundry machines, dishwashers and plug-in electric vehicles (PEV), can participate in the DR program and will be included as the model is further developed.

Preliminary results show that, by using DR, a higher share of PV can be integrated into the existing distribution system before reinforcements are required. Without DR the penetration level could reach 5.2 m^2 per building whereas with DR it could increase to about 7.8 m^2 per building. This means that, on a yearly basis, about 45% of the energy consumed can be generated from local PV systems, compared to 30% without any DR programs.[6]

5 D. Steen, et al. (2012) Price-based demand-side management for reducing peak demand in electrical distribution systems – with examples from Gothenburg, NORDAC 2012, Aalto Finland.

6 This study focuses only on the static limitations such as line loading, voltage rise and transformer loadings, while other issues like protection system and short term harmonics are not treated. Further, the heat demand is assumed to be equal in all buildings and has been estimated based on the outdoor temperature and the average heat demand for a house in that region. The possibility to shift the heat supplied to a building in time is due to the thermal inertia of a building, i.e. some energy is stored in the building materials. For the study a relatively low thermal inertia has been assumed, to avoid overestimating the potential of DR. On the other hand, the thermal model of the building is simplified and the study assumes that there exist incentives to customers to participate in the DR and that all customers have the possibility to participate.

WHAT CAN DEMAND RESPONSE DO FOR CONGESTION IN THE TRANSMISSION NETWORK?

As presented earlier in the chapter, demand response can work on different timescales and help to address different problems that can arise when introducing intermittent renewable production in the power system. One of these issues is congestion in the transmission grid (see Chapter 9). Demand response can reduce congestion by adapting the demand in a region where import or export of electricity is limited by congestion. One can see demand response as a decentralised way of managing variations, i.e. the variation is managed in the region confined by congestion, which stands in contrast to the more centralised way of investing in new transmission lines in order to spread variations over a larger geographical area. These two strategies are thus two ways to increase the economical or environmental performance of systems with large amounts of intermittent generation.

Alleviating congestion by DR is illustrated here by the same model that is used in Chapter 9. Europe is divided into fifty different regions based on bottlenecks in the transmission system, i.e. areas between which congestion is likely to occur. In the example, describing Europe in 2020, 17% of the electricity generated comes from solar or wind and CO_2 emissions are reduced by 44% compared to 1990 (see Figure 9.3).[7]

Three scenarios are presented, a reference case with no demand response, a case where 10% of the load for a region during an hour can be delayed up to six hours and one with 20% and a delay time of up to 24 hours. The effect demand response has on congestion, i.e. on differences in marginal cost of electricity between regions, is investigated. The standard deviation of the marginal costs in the fifty regions is used as an indicator of the overall congestion in the system, here referred to as System Congestion. If the standard deviation is zero the marginal costs are the same in all regions and no congestion exists. It should be noted that the System Congestion parameter only says something about the relative marginal costs between regions, i.e. demand response could lower marginal costs in two regions, reducing total system cost, but the value of System Congestion could stay the same. System Congestion is thus only an indicator of reduced congestion and not of a change in total system cost.

In Figure 10.5, the System Congestion during three winter weeks is shown as well as the total European wind power output for the same period. As can be seen, the System Congestion is largest during peak load hours. This is mainly due to the fact that the desired power flow between areas is higher when the demand is high. Further it can be seen that the System Congestion generally increases for hours with high wind power production. As discussed in Chapter 9, the areas with high wind power production cannot export enough electricity to the neighbouring areas due to congestion resulting in large difference in the marginal electricity cost between areas. For the 10% and 6 hour DR case, System Congestion is somewhat reduced during peak load hours. However, the trend seen in the reference case is still there. With 20% and 24 hour DR, System Congestion is substantially

7 Göransson, L. et al. (2013), Linkages between demand-side management and congestion in the European electricity transmission system, submitted for publication.

reduced both for peak load hours and non-peak load hours, indicating that the delay time and DR volume plays an important role when DR are being used to reduce congestion in the power system. It can also be noted that even in the most optimistic DR case, System Congestion is still more prominent during periods with high wind power production.

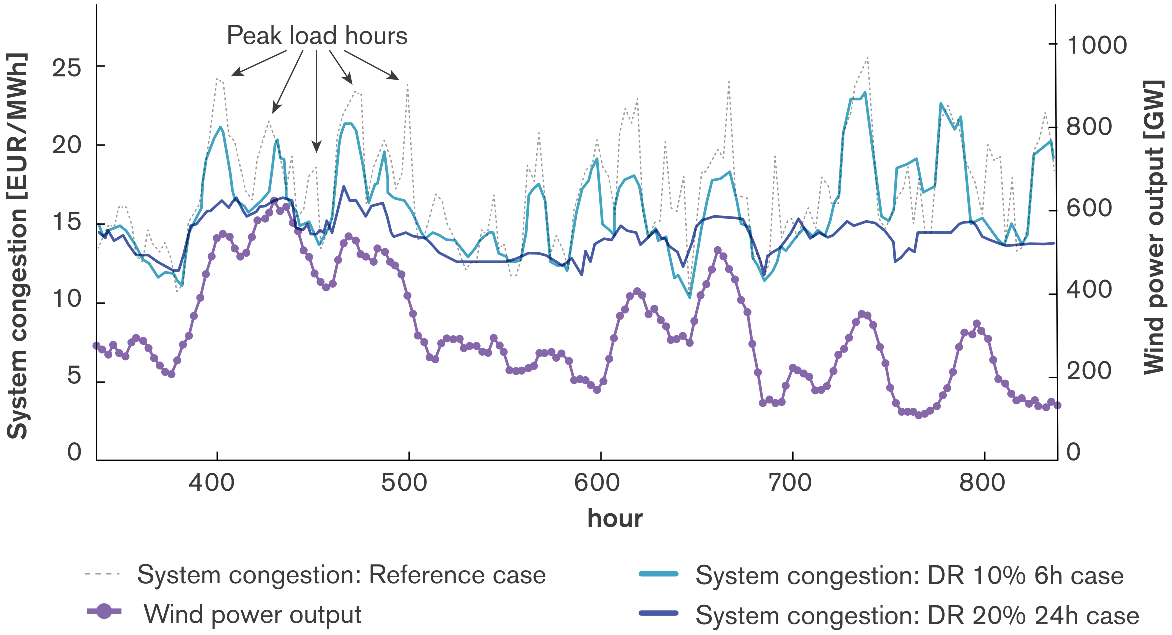

Figure 10.5 System Congestion and total wind power generation for three winter weeks. Three cases are shown one with no DR and two with DR, for both DR cases System Congestion is reduced.

Three types of congestion patterns are identified. In the following, we analyse the ability of demand response to alleviate each type.

The first type is peak hour congestion. Congestion between regions arises during peak load hours forcing the importing region to switch to a more expensive marginal generation technology. Such congestion occurs primarily between regions dominated by thermal generation. Demand response can shift load away from peak hours to off-peak hours, resulting in lower System Congestion during peak hours and higher utilisation of transmission lines during off-peak hours.

The second type is low load hour congestion. Congestion arises between regions where one region has a high share of intermittent generation relative to its load and the other region has a load that is large compared to export possibilities of the transmission line. During hours of low load and high wind power generation congestion arises between such regions. For these hours wind power is setting the marginal price in the region with a high share of wind production. However, limits in the transmission line prevent enough electricity to be exported to change the marginal generation technology in the importing region. Implementing demand response in such a case has a low impact on congestion as the controllable load is small compared to the generated wind power in the wind power region. This means that shifting load to hours with high wind power generation will not affect marginal production technology in the region during these hours and thus the congestion remains.

The third type of congestion is all hour congestion. In these cases congestion occurs at both peak and low load hours. This occurs between regions where the marginal cost in one region is always lower than in the other resulting in a constant flow of electricity from the low cost to the high cost region. This occurs if the two trading regions have fundamentally different supply structures, e.g. nuclear power dominating in France and natural gas dominating in Spain. Implementation of demand response in these cases can reduce marginal prices in each region individually, and shifting away load for some hours can reduce the difference in marginal cost between regions. However, as there are no hours without congestion the shift will typically result in an increased marginal cost difference in the hour to which demand was shifted. How this affects the average congestion between the regions depends on the individual supply structures of the regions, although typically the reduction is small.

In conclusion DR can have an effect on congestion, although its impact on congestion due to wind power appears to be low. However, DR needs to be considered in plans for investments in transmission lines aiming at integration of larger amounts of renewables.

CONCLUDING REMARKS

Generally, DR is about giving electricity consumers enough incentives to change the way they are using electricity. Traditionally, DR has been used to flatten the load profile to decrease the need for expensive peak power plants and avoid grid extensions but it could also be an effective way to facilitate the integration of intermittent renewables.

It has been shown that DR could be used to increase the maximal penetration level of renewables in distribution systems and to some extent reduce congestion in transmission systems with high shares of renewables. However, DR can mainly be effective to manage integration challenges on the short to medium time ranges, i.e. from milliseconds up to hours or days. For the short time range automatic demand response would likely be preferable while alternatives such as real time pricing can be used for the medium time range. On longer time scales other solutions such as energy storage or grid extension may be necessary (or more visionary DSM measures such as varying industrial production over seasons). In order to utilise the available DR potential the demand side needs to be integrated into a communications network, and hence, DR may co-evolve with smart grids and the internet of things.

11

INTERMITTENT RENEWABLES, THERMAL POWER AND HYDROPOWER - COMPLEMENTS OR COMPETITORS?

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INTRODUCTION

Around 80% of the electricity demand in the world is still supplied by fossil fuelled power or nuclear, i.e. thermal generation. Wind and solar power is integrated into the electricity generation systems to decrease the amount of carbon dioxide emissions associated with the generation of electricity as well as to enhance security of supply. Wind and solar power plants differ from thermal generation in two important ways: they have very low running costs (and high capital costs) and a generation level that depends on external elements. Due to the low running costs there are strong economic incentives for the employment of wind and solar power to supply the electricity demand once the capacity has been put in place.. However, the share of the load that can be supplied by wind and solar power in a certain hour or second varies irregularly since it depends on prevailing wind speeds, solar irradiation and cloudiness.

Thermal units are most efficiently run continuously at rated power. However, in a mixed renewable-thermal system they may have to compensate for fluctuations in wind and solar generation. Thus, depending on the characteristics of the renewable-thermal system, part of the decrease in fuel costs and emissions realised by wind and solar power may be offset by a reduced efficiency in the operation of the thermal plants. This chapter discusses the interaction between intermittent renewable power and thermal power, and investigates briefly the impact of including a more controllable renewable source such as hydropower in these mixed systems.[1]

THE OPERATION OF A THERMAL POWER SYSTEM – MEETING VARIATIONS IN LOAD

The electricity generation system is designed to meet the load at any instant in time. The demand for electricity generally varies in a regular pattern between night and day, workday and weekend, season to season (Figure 11.1). In a thermal system, the demand which remain throughout the week is typically met by thermal units deigned for continuous power production. These units have low running costs at rated power, but poor part load properties and high start-up costs. We will refer to them as base load units. The additional demand during day-time is met by thermal units with higher running costs but better part load properties and lower start-up costs, i.e. peak load units.

In each power system there is a balance between base load and peak load capacity to match the load variations of that specific system. Since load variations follow a regular diurnal pattern it is fairly well known when and to what extent different plants need to be in operation.

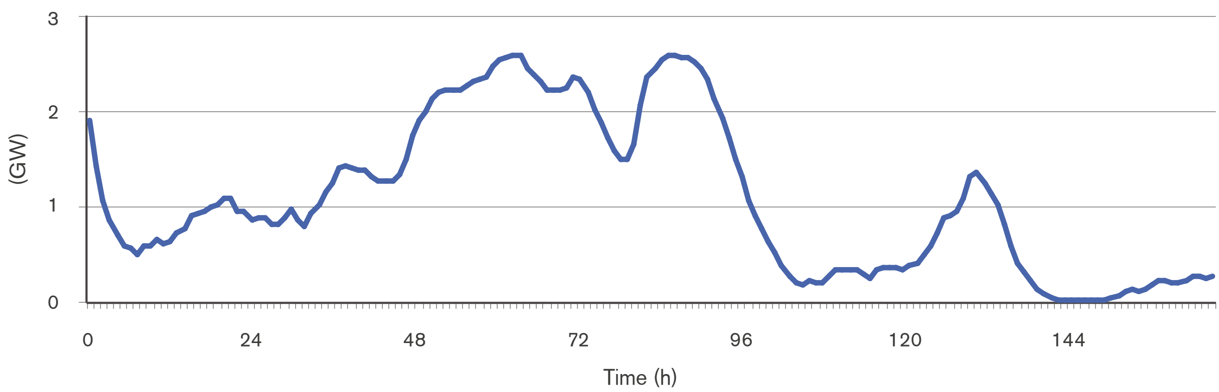

Figure 11.1. Total hourly load in western Denmark the first week in January 2013. Source: Energinet (2013)

A reduction in load or an increase in wind and solar power generation in a renewable-thermal power system that uses no active strategy for variation management (i.e. storage or demand side management, see Chapter 5, 9, 10 and 12) can be managed (passively) in three different ways: part load operation of thermal units, stopping thermal units, or curtailing power from renewable units.

The choice of variation management strategy depends on the properties of the thermal units which are in operation and the duration of the variation. In a power system where the total system cost to meet the load is minimised, the variation management strategy associated with the lowest cost is chosen. If, for example, the output of wind power and some large base load unit exceeds demand for one

1 See Chapters 3 and 4 on the characteristics and availability of different renewable energy flows.

hour, curtailment of wind power, or possibly some curtailment in combination with part load of the thermal unit, might be the solution associated with the lowest total system cost. If the same situation lasts for half a day, stopping the thermal unit might be preferable.

Three properties of thermal units will have an immediate impact on the scheduling of the units: the minimum load level, the start-up time and the start-up cost. The start-up time is either measured as the time it takes to warm up a unit before it reaches a state where electricity can be delivered to the grid (called 'time until synchronisation') or as the time before it delivers at rated power ('time until full production'). In both cases, the start-up time ultimately depends on the capacity of the unit, the power plant technology and the time during which the unit has been idle. Small gas turbines have relatively short start-up times, in the range of 15 minutes (time until synchronisation), and large steam turbines have long start-up times, in the range of several hours (up to three days for supercritical coal, see Table 11.1). If a large unit has been idle only for a few hours, materials might still be warm and the start-up time can be reduced.

The costs associated with starting a thermal unit are a result of the cost of the fuel required during the warm-up phase and the accelerated component aging due to the stresses on the plant from temperature changes.[2] Intertek Aptech have summarised cycling costs of thermal units in the US for NREL[3]. A summary of their lower bound costs can be found in Table 11.1.

Table 11.1 Typical cycling costs of thermal units in the US in operation in 2012.a Source: Kumar, N. et al. (2012).

	Hot start [EUR/MW]	Warm start [EUR/MW]	Cold start [EUR/MW]	Startup time [h]
COAL				
Super critical	30	40	70	12 - 72
Large sub critical	30	50	70	12 - 40
Small sub critical	40	70	70	4 - 24
GAS				
Combined Cycle	20	30	50	5 - 40
Steam	20	30	40	4 - 48
Large Frame CT	20	20	30	2 - 3
Areo Derivative CT	10	10	10	0 - 1

[a] USD is converted to EUR with an exchange rate of 0.75.

One alternative to shutting down and restarting a thermal unit is to reduce the load in one or several units. The load reduction in each unit is restricted by the maximum load turn-down ratio. The minimum load level of a thermal unit depends on the power plant technology and the fuel used in combustion units. For example, the minimum load level reported for Danish units range from 20% of rated power

2 It has been shown that the combined effect of creep, due to base load operation, and fatigue, due to cycling (start-up and shutdown and load following operation), can significantly reduce the lifetime of materials commonly used in fossil fuel power plants in comparison to creep alone. Lefton et al. (1995), Managing utility power plant assets to economically optimize power plant cycling costs, life and reliability, Aptech Engineering Services, Inc., Sunnyvale, California, USA.
3 Kumar et al. (2012)Power Plant Cycling Costs, Aptech Engineering Services,for NREL Bolulder, Colorado, USA

for gas- and oil-fired steam power plants to 70% of rated power for waste power plants. Minimum load level of coal fired power plants range from 35% to 50% of rated power depending on technology.[4]

A low minimum load level is of great importance for any load following thermal unit since it allows for operation under a wide range of load situations and reduce the need for cycling. Size matters when it comes to cycling properties, because small units have a low minimum load level in absolute terms. It may be possible to find a combination of small units to suit the load situation at hand while only cycling a few of the units, while a large unit would have to choose between shutting down (and later restart) the whole capacity or deliver power at a price below running costs.

Running thermal units at part load is associated with an increase in costs and emissions per generated kWh, since the efficiency decreases with the load level. The rate of the decrease in efficiency depends on the power plant technology and the level to which the load is reduced. The rate of decrease in efficiency is generally lower at high load levels than at low load levels. The efficiency of combined cycle plants (CC) is typically more sensitive to a load level decrease the than the efficiency of steam plants since gas turbines are sensitive to part load operation.

WIND POWER REDUCES THE COMPETITIVENESS OF BASE LOAD UNITS

In contrast to load variations, wind power variations follow no given pattern (compare Figure 11.1 and 11.2). The power output of a single wind turbine can vary rapidly between zero and full production. However, since the power generated by one turbine is small relative to the capacity of a thermal unit, such fluctuations have negligible impact on the generation pattern of the thermal units in the overall system.

With several wind farms in a power system, the total possible variation in power output can add up to capacities corresponding to the thermal units and influence the overall generation pattern. The power output of the aggregated wind power is, however, quite different from the power output of a single turbine. Wind speeds depend on weather patterns as well as the landscape around the wind turbines (i.e. roughness of the ground, sea breeze etc.). The greater the difference is in weather patterns and environmental conditions between the locations of the wind turbines, the lower the correlation in power output.

In a power system with geographically dispersed wind farms, the effect of local environmental conditions on power output will be reduced. Since it takes some time for a weather front to pass a region, the effect of weather patterns will be delayed from one farm to another, and the alteration in aggregated power output thus takes place over a couple of hours rather than instantaneously. This effect is referred to as power smoothing.[5] Western Denmark is a typical example of a region with dispersed wind power generation. The aggregated wind power output for this region during one week in January can be found in Figure 11.2. Variations in the range of the capacity of thermal units do occur. For example, between hour

4 Energinet (2007) Technical Regulations for Thermal Power Station Units of 1.5 MW and higher.
5 Manwell et al. (2005) Wind energy explained, Wiley.

92 and 105 the wind power generation decreases by 2.3 GW. However, this large shift in output power is not instantaneous, but takes place over several hours.

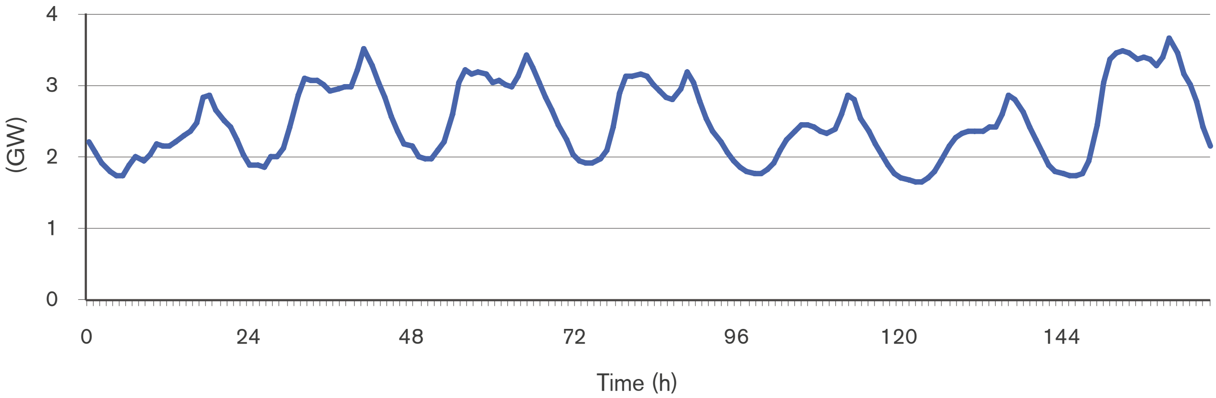

Figure 11.2 Hourly wind power generation in western Denmark during the first week in January 2013. Source Energinet (2013)

For the thermal units, it is the aggregated impact of wind power and the total load which is of importance. On a seasonal basis, there is a positive correlation between wind power generation and load in northern Europe, i.e. it is windier in wintertime when there is a demand for electricity for heating purposes. However, on an hour to hour basis, the correlation between wind power and load is generally low. Maxima and minima of wind power output on the one hand and electricity demand on the other may overlap at any time of the year, resulting in large variations in load on the thermal units. At times when wind power output is high and demand is low, systems with wind power in the range of 20% grid penetration or higher might face situations where power generation exceeds demand. Without storage in the system, some of the wind power generated will then have to be curtailed. With base load capacity with very high start-up costs (Table 11.1), situations where curtailment is preferable will arise more frequently.

Studies using models of the power system of western Denmark suggests that wind power variation influences the relative competitiveness of different thermal power plants.[6] In general, simulations show that an increase in the amount of wind power reduces the duration of periods of constant production. Then units with high start-up costs and high minimum load level (i.e. base load units) will be used less. This result might seem trivial. However, high start-up costs and high minimum load levels are common properties of units with low running costs designed for base load production. Thus, low running costs compete against flexibility and in a system with significant wind power capacity the unit with the lowest running costs is not necessarily the best complement.

As an illustration, Figure 11.3 gives the modelled capacity factors of Enstedtsverket and Fynsverket 2, at different wind penetration levels.[7] The system operation has been scheduled so as to minimise the system running costs while including or omitting start-up costs and minimum load level constraints of the thermal units.

6 Göransson, L. and F. Johnsson (2009). "Dispatch modeling of a regional power generation system - Integrating wind power." Renewable Energy 34(4): 1040-1049

7 The capacity factor measures the utilisation of a power plant, and is calculated as the ratio between the actual annual electricity generation and the maximum annual electricity generation at rated power.

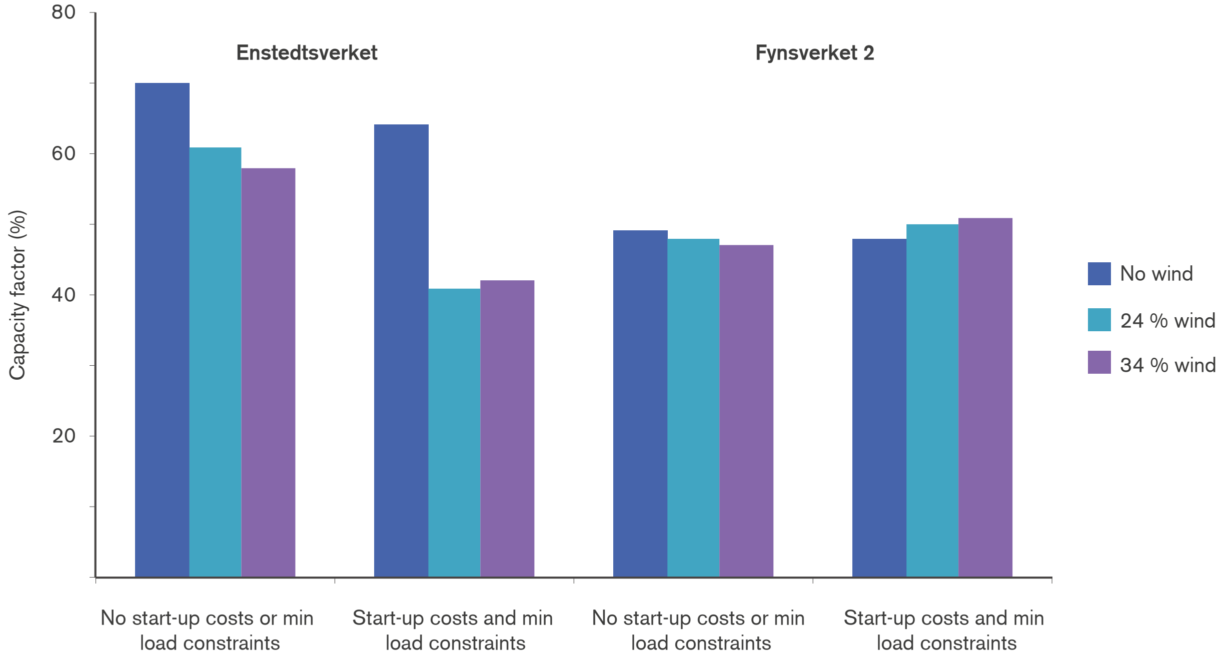

Figure 11.3 Capacity factor of Enstedtsverket and Fynsverket 2 with and without including start-up costs and minimum load level constraints, as wind power supply an increasing share of the demand for electricity.

Enstedtsverket is the single largest thermal unit in the western Denmark system. It has the lowest running costs in the system and if start-up costs and minimum load level constraints are omitted, Enstedtsveket has the highest capacity factor of the thermal units in the system at all wind power penetration levels. However, Enstedsverket also has the highest start-up cost (in absolute terms) and the highest minimum load level. Consequently, Figure 11.3 shows that if start-up costs and minimum load level constraints are included, the capacity factor goes down rapidly in the cases with high wind power penetration.

Fynsverket 2 has higher running costs than Enstedtsverket, but also significantly lower minimum load level. If cycling costs and minimum load level constraints are omitted, the operation of Fynsverket 2 would have been reduced, although to less extent than Enstedsverket due to a lower initial capacity factor. However, if cycling costs and minimum load level constraints are accounted for, the capacity factor of Fynsverket 2 increases as it replaces units with worse cycling properties such as Enstedsverket. The variations in wind power production have thus altered the dispatch order of the thermal units between the no wind and the wind cases, favouring units with more flexible properties over the unit with the lowest running costs.

Several studies have investigated the cost of cycling thermal generation in electricity generation systems with 20% wind power and found that they are small compared to total system cost (i.e. a few percent of the running costs and start-up costs).[8] At this penetration level, cycling costs are also found to be small compared to the reduction in fuel costs realised by the inclusion of wind generation.

8 Göransson, L. and F. Johnsson (2009). "Dispatch modeling of a regional power generation system - Integrating wind power." Renewable Energy 34(4): 1040-1049. Holttinen et al. (2009) Design and operation of power systems with large amounts of wind power, IEA Wind task 25, Finland, Jordan and Venkataraman (2012). Analysis of Cycling Costs in Western Wind and Solar Integration Study, NREL; Boulder, Colorado, USA

SOLAR POWER REDUCES PEAK LOAD UNIT PRODUCTION HOURS

From an aggregated perspective, solar power generation is highly correlated with demand. High load hours typically occur during daytime when the sun is up and solar power can be generated.[9] In southern Europe and southern US there is even a direct physical relation between solar power and electricity demand; when it is sunny the electric load from air-conditioning is high while solar power delivers at full capacity. In the absence of sun, the electric load from cooling devices is also reduced. Figure 11.4 illustrates the general correlation between the demand for electricity and solar generation for a low voltage grid in Germany.[10]

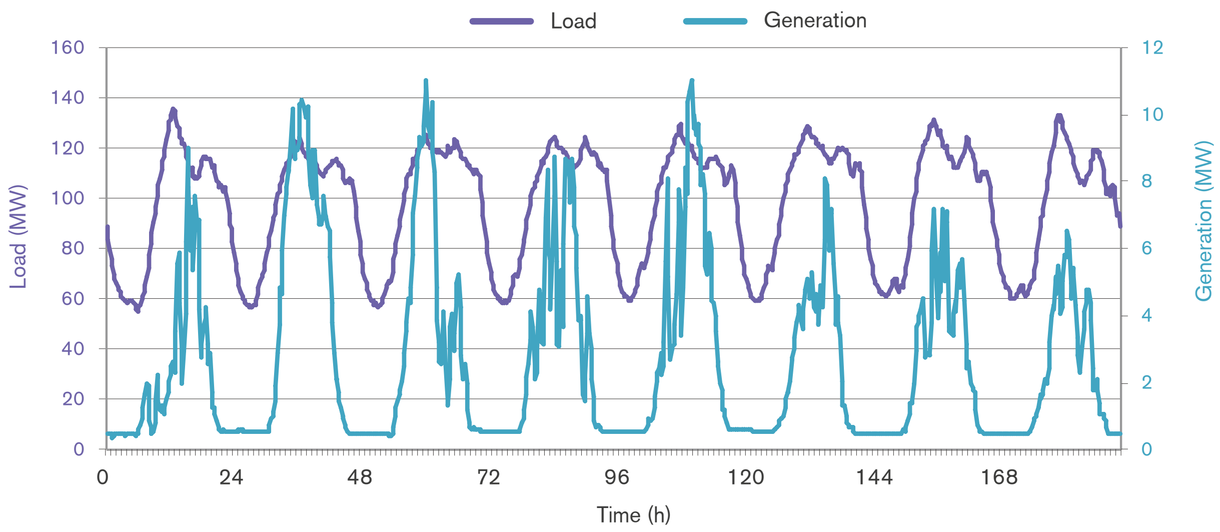

Figure 11.4 Hourly generation (infeed) and load on a low voltage grid in Germany. Source: ENERVIE AssetNetWork GmbH (2013)

During peak load hours, peak load and mid-merit load is in operation as well as base load units. Solar power production will replace the units with the highest running costs first, in this case typically peak load units with good flexible properties. If all units in operation are subject to significant start-up costs, it may suffice to reduce operation in several units to part load operation to accommodate the solar power generated. Solar power can thus be integrated to some extent before it causes start-up costs of any significance.

THE REMAINING NEED FOR CAPACITY

As the amount of wind and solar power increases in the system, the operation hours of thermal units will be reduced. Non-marginal levels of wind and solar power in the system will also affect electricity prices. Since wind and solar power have very low running costs they will cause electricity prices to drop under sunny and windy hours. The combination of reduced operation hours and periodically decreased electricity prices will reduce the returns on investments in technologies with high investment costs, such as nuclear power and large coal-fired power plants. However, in the absence of very large storage capacity, there will still be

9 In a distribution grid supporting only private households the load pattern is typically less correlated with solar power production, with higher demand in mornings and evenings (see Chapter 9).
10 ENERVIE Asset Net Work GmbH (2013) Accessed 2013-05-15

a need for capacity to supply the load during hours of poor wind and solar conditions. Large interconnected systems and combined investments in wind and solar power reduce the number of hours of low wind and solar power generation, but such hours will still occur. On an energy-only market, where electricity producers are paid based on the amount of energy they deliver to the grid rather than for the capacity which they maintain available for production, hours of low wind and solar power generation will be coupled to high costs of electricity. These hours will bring profit to peak load units and are also likely to stimulate demand side management, or demand response (see Chapter 10) and investment in storage (or possibly fuel production, Chapter 12).

There is an ongoing discussion on whether very large fluctuations in electricity prices will be tolerated by electricity consumers. An alternative would be a capacity market where you are paid for capacity which is kept available to the system and/or a market for energy storage.[11]

HYDROPOWER WITH STORAGE AS A COMPLEMENT TO INTERMITTENT RENEWABLES

Similar to thermal units, electricity generation in hydropower plants with storage are not immediately dependent on weather conditions and can thus meet variations in load and wind and solar power generation. For thermal units there is typically a trade-off between good cycling properties (i.e. low minimum load level, low start-up costs and short start-up time) and low running costs. Unlike thermal units, hydropower plants have low running costs and low cycling costs. Assuming infinite storage, the capacity factor of hydropower will remain unchanged as wind power is integrated in the system until the yearly production of wind and hydro power exceeds the yearly electricity demand of the region and its yearly export capacity. Due to storage limitations, wind and hydropower generation can exceed the electricity demand for some part of the year, with spillage of water or curtailment of wind power as a consequence.[12]

Hydropower is scheduled so as to replace the most expensive generation in the system. Since hydropower is storable, a peak load increase by one unit in a hydro dominated region, e.g. northern Sweden or southern Norway, can be compensated for by increased thermal generation at some other time in any of the neighbouring regions. Marginal costs in northern Sweden and southern Norway are thus stable at levels given by marginal costs during periods of low load in neighbouring regions.

Variation management with hydropower follows the simple principle that imported power from a region with high wind or solar power penetration (e.g. western Denmark) supplies the load of some hydro dominated regions (e.g. south Norway) during hours of low load or high wind (or solar) power production. The hydropower dominated region use hydropower both to cover domestic electricity demand and for export during peak load or low wind and solar power generation.

11 Alternatively, capacity markets may be viewed as a way for incumbent utilities to protect the value of their assets rather than a way to protect electricity consumers (see Chapters 2 and 13).

12 Note that hydropower is not available in all systems. See Chapter 3 on the relative global resource availability of solar, wind, hydropower and other renewables as well as their temporal and spatial distribution.

Figure 11.5 gives modelled yearly trade flows between northern Germany and Norway by 2020 assuming a strong wind expansion in northern Germany and transmission investments both between Germany and south Norway and internally in Germany (see Chapter 9 on the role of transmission). The figure gives that under wet year conditions, Norway exports electricity to Germany except during high wind events. Under dry year conditions, in order to maximise profits Norway imports (cheap) electricity during every low load hour to be able to export (expensive) electricity during peak load.

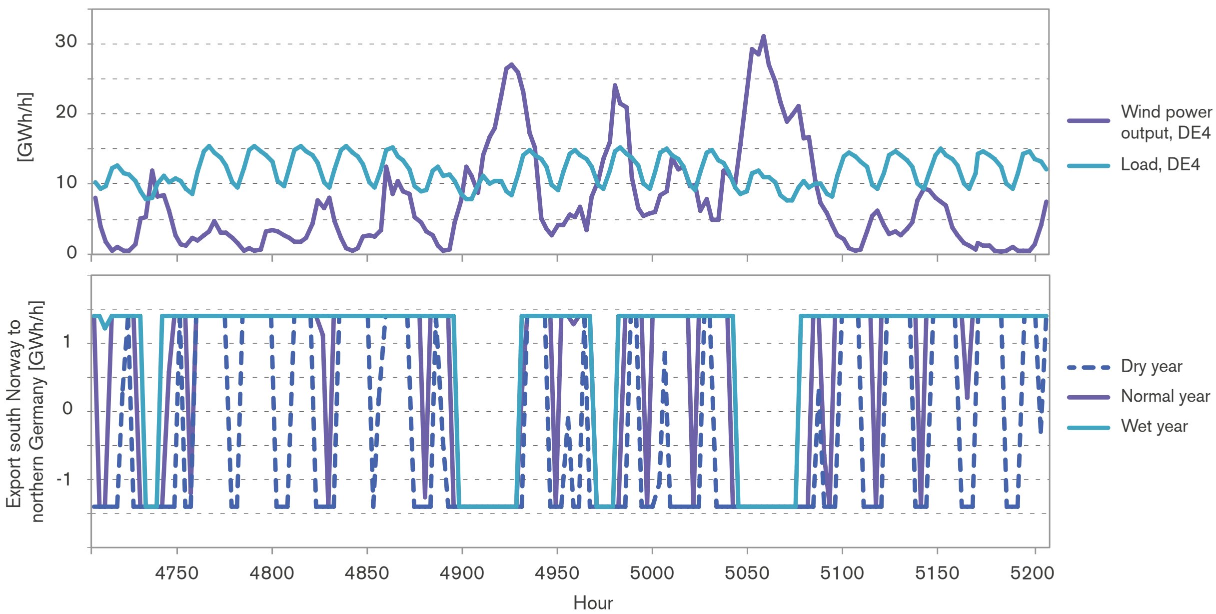

Figure 11.5 Modelled trade flows between south Norway (NO1) and northern Germany (DE4) for three weeks in spring around 2020. Source: Göransson et al. (2013)

CONCLUSIONS

Systems where wind power supply 10-20 % of the demand, cycling costs of thermal units are low. Cycling costs due to solar penetration at the same level are expected to be even lower.

Wind power generation is uncorrelated with the load and typically reduces the competitiveness of base load units whereas solar power generation is well correlated with the load and therefore typically reduces the operation hours of peak load units. Unlike thermal units, hydropower combines good cycling properties with low running costs and is therefore a good complement to intermittent renewables in general.

As the wind and solar power supply larger shares of the yearly demand for electricity, the operation hours of thermal units will decrease. However, there will still be hours of low wind and solar power generation. The need for capacity rather than energy favours thermal units with low cycling costs and low investment costs as complement to wind and solar power.

12

UTILISING EXCESS POWER: THE CASE OF ELECTROFUELS FOR TRANSPORT

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INTRODUCTION

If the production of electricity at a given moment in time is higher than demand we may talk about excess electricity.[1] It is possible to store excess electricity and storage solutions might be essential for achieving very high renewable energy shares in the energy system. The most common purpose for storing electricity is of course to convert the stored energy back to electricity when needed. Currently there are not many mature alternatives for seasonal energy storage. Pumped hydro, hydrogen and compressed air are facing challenges with geographical distribution and ecological footprint, technical limitations or low density.[2] Another option is to convert electricity into an energy carrier that can be used for other purposes, and not just as a medium for electricity storage. One possibility is to use periods of excess electricity for the production of carbon-based synthetic fuels, so called electrofuels,[3] that can be used for various purposes, e.g. for heating, as a transportation fuel or in the chemical industry for the production of plastics, textiles, medicine and fertilizers.

1 Read more about challenges related to balancing demand and supply of electricity over different time scales in Chapter 9-11
2 See Chapter 4 for an overview of energy storage options.
3 The concept of converting electricity to synthetic methane is sometimes also named “Power-to-Gas” or “carbon recycling” and the product can for example be denoted e-gas, e-methane, synthetic natural gas (SNG) or sun-fuels. In this chapter electrofuels is an umbrella term for carbon-based fuels produced with electricity as the main energy source, following the definition in Nikoleris, A. & Nilsson, L. (2013). Elektrobränslen en kunskapsöversikt. Report. Lund.

One challenge, common to all energy storage technologies, is to be economically viable in spite of the fact that excess, or low priced, electricity will likely be available only a fraction of the time. This chapter aims to explore the challenges and opportunities of using electrofuels to utilise excess electricity. Production processes are described and costs are estimated to underpin a discussion on what is required to make electrofuels competitive with gasoline.

USAGE OF ELECTROFUELS

Electrofuels, e-methane and e-methanol, can be stored and then used in various applications in society. They can be converted back to electricity, but with electricity-to-electricity conversion efficiency of only some 35%, other applications could be more attractive. E-methane can be fed directly into the current natural gas infrastructure and used where natural gas is used today, for example as feedstock in the chemical industry, as source of heat in domestic and industrial applications, or as transport fuel. Also e-methanol can be used in the chemical industry and as a transport fuel. A challenge for the transport sector is to find a fuel that can be used in all, or at least many, types of transport modes, that is based on renewable energy, and that do not suffer from the supply constraints and environmental and social issues related to biofuels. Electric vehicles have high energy efficiency (up to 90%) and the electricity use per driven vehicle distance is approximately five times higher for electrofuels compared to electric vehicles. On the other hand electric vehicles are facing difficulties with costly batteries and short driving range. In particular, aviation, shipping and long-distance road transport may have difficulties in relying on fuel cells and batteries (see Figure 12.1).

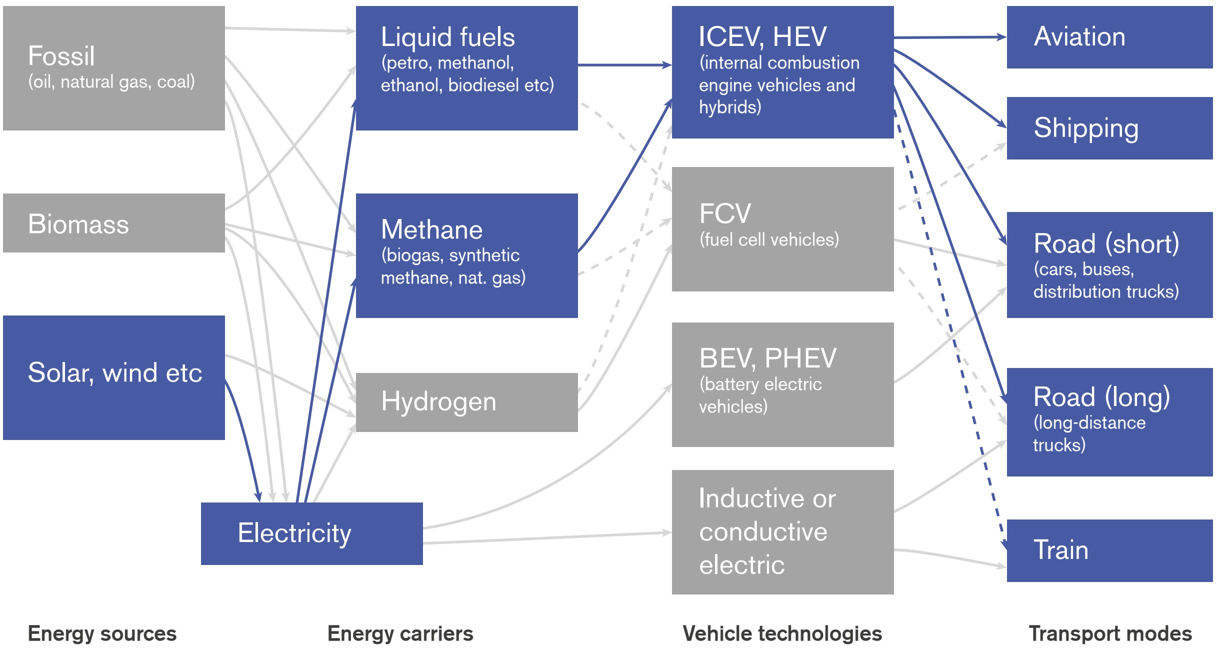

Figure 12.1. Possible energy flows and engine technology options for different transport modes. Blue boxes and arrows mark the electrofuel options utilising renewable power.

Hydrogen, produced from splitting water with renewable electricity,[4] is less costly to produce per energy unit compared to electrofuels but is by many considered to be unpractical in transport applications, e.g. due to the low volumetric energy density, safety issues and the need for a new infrastructure in the distribution chain. Electrofuels may then be an attractive option since there is no need for advanced vehicle technologies or major changes of infrastructure and they are suitable also for aviation and shipping. Although, compared to electric or hydrogen vehicles, combustion of hydrocarbons releases other emissions than CO_2, e.g. particles, NO_x and CO, which contributes to air pollution and the formation of ground-level ozone.

Current interest in electrofuels from the vehicle industry is demonstrated by Audi that has invested in a 6 MW electrofuel plant in Germany that uses solar electricity to produce e-methane.[5] Volkswagen recently highlighted e-methane as an important future complement to conventional natural gas and biomass based methane.[6] Also in the shipping sector, the company Stena Line sees methanol as a possible replacer of oil and has converted the auxiliary engine at Stena Scanrail to DME (converted on-board from methanol) and is planning to convert 25 of 34 ferries to run on methanol during the next few years.[7] In a long-term scenario they see e-methanol as a possible replacement of current fossil based methanol.

Another example of current electrofuel production is the Icelandic renewable e-methanol company, Carbon Recycling International, that built their first commercial plant in 2012 with a capacity to produce more than 5 million litres e-methanol per year for the purpose of blending 3% methanol in gasoline. The CO_2 feedstock and the power for producing electrofuels are both supplied by a geothermal power plant and the electricity prices are very low.[8] If larger volumes are produced, the excess e-methanol will be exported to Europe.

PRODUCTION OPTIONS AND COST ESTIMATES

Several steps are needed to produce electrofuels (Figure 12.2): (i) producing hydrogen from water (electrolysis), (ii) capturing CO_2, and (iii) mixing hydrogen and CO_2 to form different types of electrofuels (the Sabatier reaction).

Producing hydrogen through electrolysis is a commercially available technology used in e.g. the chemical industry. In an electrolyser, electricity is used to split water into oxygen and hydrogen. Hydrogen production via electrolysis can instantaneously increase, decrease, and stop production rates, and thereby efficiently meet rapid variations of electricity supply. There are three main types of electrolysers: alkaline (AEC), proton exchange membrane (PEM) and solid oxide (SOEC) electrolysers. Commercial AEC electrolysers have conversion efficiencies of 60-70%. High-temperature SOECs, which are expected to enter the market in

4 The energy for water splitting can also be supplied from solar radiation directly or from high temperature heat generated from concentrated solar radiation, without an intermediate step of electricity production.

5 Audi e-gas. Energy turnaround in the tank. www.audi.com/content/com/brand/en/vorsprung_durch_technik/content/2013/10/energy-turnaround-in-the-tank.html

6 Volkswagen Group Strategies. 0% Emission, 100% emotions, The road to Electromobility. Available at: www.volkswagenag.com/content/vwcorp/info_center/en/publications/2013/01/0_Emissions_100_Emotions.bin.html/binarystorageitem/file/Final_VW_EMob_20120514_komplett_EN.pdf

7 Ny teknik. Stena Line satsar på methanol. http://www.nyteknik.se/nyheter/fordon_motor/fartyg/article3667269.ece access 2013-12-03.

8 Carbon Recycling International (CRI). http://www.carbonrecycling.is/. Access 2013-12-03.

2015-2020, are expected to reach conversion efficiencies of 80-90%. PEM electrolysers have similar conversion efficiency as AEC, use more expensive materials, and will most probably not be as cost-effective as SOEC.

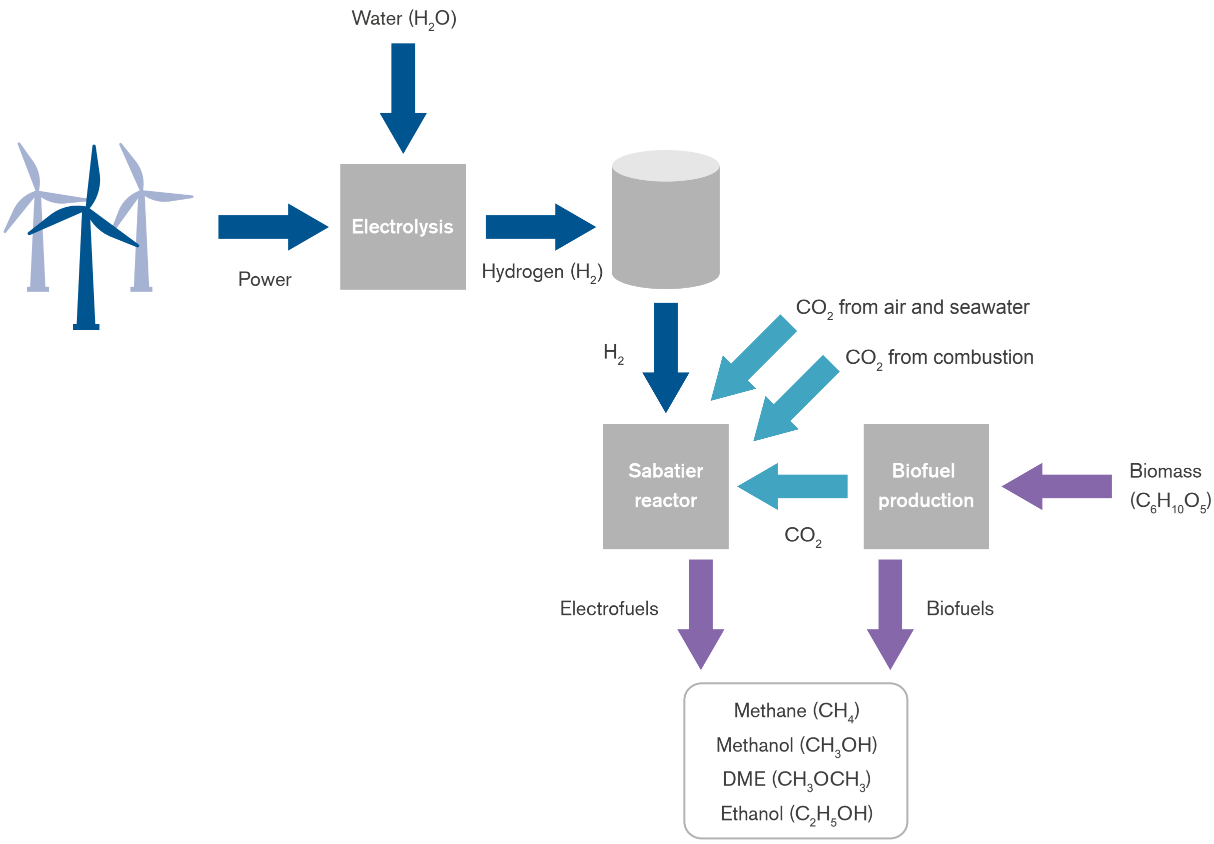

Figure 12.2. Process steps in the production of electrofuels where the main reaction occurs in the Sabatier reactor where CO_2 and H_2 form different types of electrofuels. The CO_2 can be derived from different carbon sources.

While the cost of electrolysers currently lies in the range of 600-1500 EUR/kW, it is estimated to drop to 250-500 EUR/kW in coming years.[9] In Figure 12.3, a cost estimate of hydrogen production is presented for different electricity prices and capacity factors (the ratio of the annual production and the maximum production capacity). We assume an energy efficiency of 80%, and an electrolyser investment cost of 400 EUR/kW. It can be noted that at capacity factors above approximately 15% the hydrogen production cost is rather similar for a given electricity price.

The carbon dioxide can come from many sources including various industrial processes giving rise to excess CO_2, e.g. biofuel production facilities, natural gas processing, flue gases from fossil and biomass combustion plants, steel plants, oil refineries and other chemical plants, geothermal activity, air and seawater. The concentration of CO_2 in the source is of great importance for costs and present commercial facilities use sources with high CO_2 concentrations.

In biofuel production, e.g. by fermentation of sugar into ethanol, anaerobic digestion of household waste into biogas or gasification of biomass into methane, considerable amounts of CO_2 are produced as a by-product. The off-gases from

9 The cost and efficiency numbers for hydrogen production are taken from estimations by Fusch et al. (2012) Technology overview on electricity Storage, Parfomak et al. (2012) Energy Storage for Power Grids and Transportation, IEA (2007) Hydrogen Production & Distribution, and NREL (2009) Current State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis.

biofuel plants, as well as from ammonia plants, are more or less pure streams of CO_2. One study claims that methane production from biomass can more than double if the CO_2 released in the process is allowed to react with hydrogen.[10] Other studies confirm that 26-80% of the carbon in the feedstock of biofuel plants is released as pure CO_2.[11] The CO_2 capturing cost with a pure CO_2 stream can be low and in most cases depends on transport distances. The capture technology does not have to be much more than a pipe into the Sabatier reaction process and the capturing cost is estimated to lie in a range from a negligible cost up to approximately 7 EUR/ton CO_2.

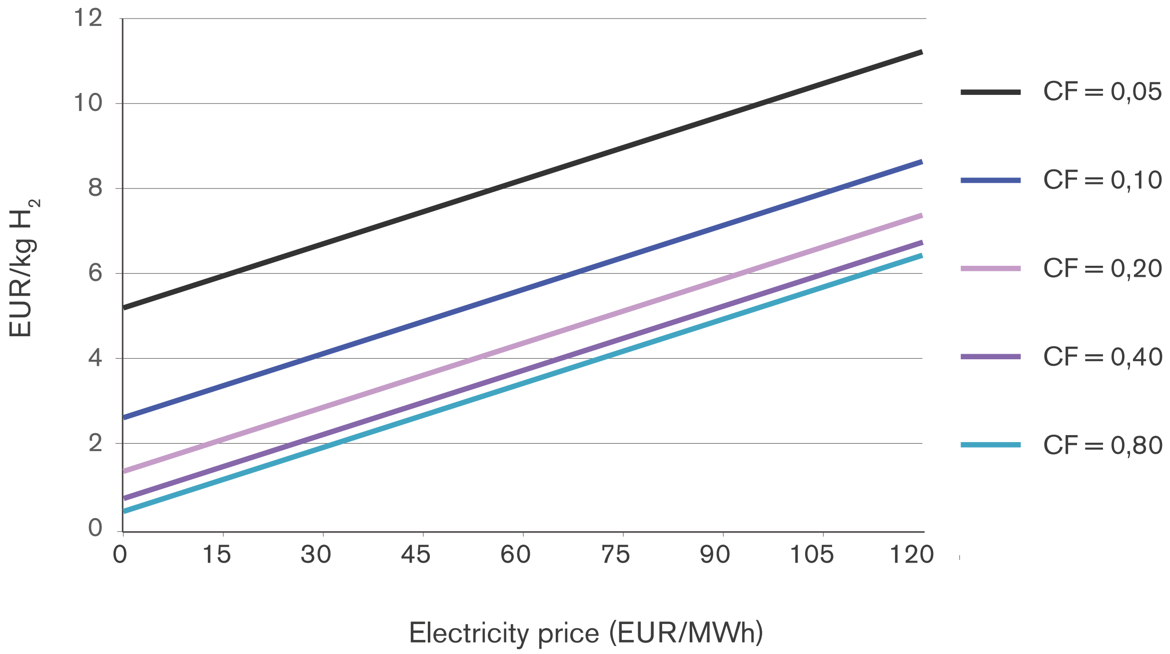

Figure 12.3 Hydrogen production costs depending on the electricity price and the share of maximum conversion capacity that the electrolyser runs per year, i.e. its capacity factor (CF). The conversion efficiency is assumed to be 80% and the electrolyser investment cost is set to 400 EUR/kW.

Flue gases from fossil or biomass combustion plants have a CO_2 concentration of 3-15%. Therefore, an extra purification step is needed before the gas can be mixed with hydrogen in the Sabatier reactor. Capturing CO_2 from flue gases can be done by three different technologies: post-combustion, pre-combustion and oxy-fuel combustion. By looking at 50 engineering studies of CO_2 capture installations at power plants, the International Energy Agency has estimated that the capturing cost at power plants ranges from 15 to 60 EUR/ton CO_2 depending on capturing technology and type of fossil fuel.[12] The capturing cost might be slightly higher for biomass power plants due to their smaller size.

The CO_2 concentration in air is approximately 400 ppm and it would require 2-4 times more energy to extract the CO_2 from air compared to flue gases. Strong bases such as NaOH, KOH and $Ca(OH)_2$ can effectively scrub CO_2 out of the

10 Mohseni ,F. (2012) Power to Gas- Bridging Renewable Electricity to the Transport Sector. KTH Royal Institute of Technology. Stockholm.
11 Luckow, P. et al. (2010). Biomass Energy for Transport and Electricity: Large Scale Utilization Under Low CO_2 Concentration Scenarios. U.S. Department of Energy. United States of America.
12 International Energy Agency (EIA) (2011) Cost and Performance of Carbon dioxide Capture from Power Generation.

atmosphere, but the regeneration of the bases is an energy intensive process, and other alternative materials that might be more energy efficient are under development. Different techniques and materials have been proposed and many designs are technically feasible. However, all are still in a very early development phase, and more research and pilot plants are needed to optimise the technology. The cost estimations are uncertain but fall in the range of 150-1250 EUR/ton CO_2.[13] A couple of start-up companies have provided prototypes of carbon capture plants from air. The company Air Fuel Synthesis built a demonstration plant in 2012 and produces 5-10 litres per day of synthetic fuels from air-captured CO_2 and hydrogen.[14]

Carbon capture from seawater might also be an option. The concentration of dissolved CO_2 in seawater is approximately 140 times higher than in air, but only 2-3% of the CO_2 in seawater can efficiently be used for fuel production.[15] The US Navy has shown interest in developing technology for extracting CO_2 from seawater with the purpose of producing synthetic aviation fuel at sea using electricity generated from nuclear energy. The capturing costs are expected to be in the same order of magnitude as for air capture technologies.

Electrofuels, e.g. e-methanol or e-methane, is produced by feeding hydrogen and CO_2 into a Sabatier reactor, see Figure 12.1. The Sabatier reactions for e-methane (CH_4) and e-methanol (CH_3OH) are:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O + \text{energy}$$

$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O + \text{energy}$$

Small molecules, like methanol and methane, are preferable since more complex molecules require additional process steps, which lead to efficiency losses. The technique of synthesising e-methane from CO_2 and water has been known since the beginning of the twentieth century, and is currently commercially used in many industrial applications, like ammonia production. It would therefore be relatively easy to implement the technology for fuel production at a commercial scale. In the process, 90% of the carbon in the CO_2 stream form e-methane. For e-methanol the conversion efficiency is lower and the reaction requires high pressure and a recycling of non-reacted CO_2. Catalysts are needed in the production and a variety of commercial catalysts are available. The process equipment costs are estimated at 140 EUR/kW for the Sabatier reactor, 2 EUR/kW for the catalyst and 4 EUR/GJ for the synthetic methane storage (the methanol storage cost is approximately a third of this).[16] Thus, the Sabatier reactor accounts for approximately a fifth of the capital cost (compare the electrolyser cost above). In Table 12.1 one can find an overview of the cost and availability of the technology for the different steps in the electrofuel production process just described.

13 Goeppert et al. (2012) have summarized and evaluate different articles estimating air capture costs in the article "Air as the renewable carbon source of the future: an overview of CO_2 capture from the atmosphere". Energy and Environmental Science.
14 Air fuel synthesis. http://www.airfuelsynthesis.com/home.html. Access 2013-12-03.
15 Willauer et al. (2011) 'Development of an electrochemical acidification cell for the recovery of CO_2 and H_2O from seawater', Industrial & Engineering Chemistry Research 50, 9876–9882.
16 Mohseni ,F. (2012) Power to Gas- Bridging Renewable Electricity to the Transport Sector. KTH Royal Institute of Technology. Stockholm.

The geographical localisation of the Sabatier reactor may also be of interest. Electricity, hydrogen and the final fuels are all transportable with high efficiency indicating that localisation of the Sabatier process may be determined by current infrastructure to avoid expensive infrastructure extensions. Since hydrogen is more costly to transport than carbon dioxide and electricity, the optimum localisation of a Sabatier process most likely is close to the electrolyser. Preferable locations for electrofuel production could be geographically isolated and relatively small systems (e.g. islands such as Iceland or Ireland) with a lot of renewable power production and difficulties with transmissions cables to the main land.

Table 12.1. Overview of cost estimates and availability of the technology for different steps in the electrofuel production process. All costs are recalculated to EUR values of 2010 (1.37 USD/EUR).

Technology	Cost estimate	Availability
Electrolysis (conv.eff 50-90%)	600-1500 EUR/kW 250-600 EUR/kW in near future	Alkaline (AEC), proton exchange membrane (PEM) are commercial, (<70%) but more efficient (80-90%) high-temperature solid oxide electrolyser cells (SOEC) are under development.
Pure CO_2 from biofuel plants	Up to 7 EUR/ton CO_2	Mature technology but few in use.
CO_2 from combustion	15-60 EUR/ton CO_2	Demonstration phase
CO_2 from air capture	150-1250 EUR/ton CO_2	Early development phase
Sabatier reactor	140 EUR/kW	Known for a long time, but few fuel production facilities
Storage e-methane	4 EUR/GJ	Mature technology
Storage e-methanol	1.5 EUR/GJ	Mature technology
Catalyst costs	2 EUR/kW	Mature technology

COST COMPETITIVENESS OF ELECTROFUELS

Under what circumstances can electrofuels compete with gasoline as transport fuel? Would it be cost-effective to run a production process only part of the year and with a low capacity factor? In the following, we try to estimate the cost of electrofuels and compare the costs of e-methanol to gasoline.

The unit cost of the electrofuel (EUR/GJ) is given by the cost of electricity and CO_2, the annuity of the investment cost, the operation and maintenance cost and the capacity factor. The investment cost is the sum of the costs of the electrolyser, Sabatier reactor and storage of synthetic fuel (see Table 12.1 for cost details).[17]

In 2013, the average electricity price for a three-year contract for a small-sized industry in Sweden was 45 EUR/MWh.[18] It is difficult to estimate how a higher penetration of wind and solar will affect the electricity price. Probably it will result

17 The annuity is calculated from the investment cost, using a discount rate of 5% and a lifetime of 25 years. It is, further, assumed that the stack has to be replaced every 7th year, i.e. three times, at 33% of the original purchase cost. The operation and maintenance cost is estimated at 4% of the total investment cost.

18 Statistics Sweden (2013). Prices on electricity and transmission of electricity

in more rapid price variations including more frequent periods with low electricity prices, due to variation in weather conditions (Chapter 9 and 11). With electrofuels produced at large-scale, high wind and solar penetrations in the vicinity of 40-50%, will however most likely be needed in order to get repeatable periods of low electricity prices. We have chosen to make calculations based on an electricity price of 0, 30 and 50 EUR/MWh. The zero case corresponds to a situation with a major electricity surplus part time of the year.

The cost of the electrolyser and its conversion efficiency are assumed to be 400 EUR/kW and 80%, respectively. The total investment cost over a 25 year lifetime including the electrolyser, three stack replacements, the Sabatier reactor and the fuel storage, is assumed to be 950 EUR/kW. In our baseline case we assume that the carbon needed in the electrofuel production comes from pure streams of CO_2 that easily can be connected to the Sabatier process and thus available at low cost. As a baseline, the cost of capturing CO_2 is assumed to be 7 EUR/ton CO_2.

In Figure 12.4 the resulting production cost of e-methanol in EUR per litre gasoline equivalents is shown for different capacity factors and different electricity prices. The crude oil price has increased drastically during the last decade, except from a drop in 2009. In 2013, the oil price fluctuated between 96 and 110 USD/barrel. Here we compare to crude oil prices of 50, 100 and 150 USD/barrel.

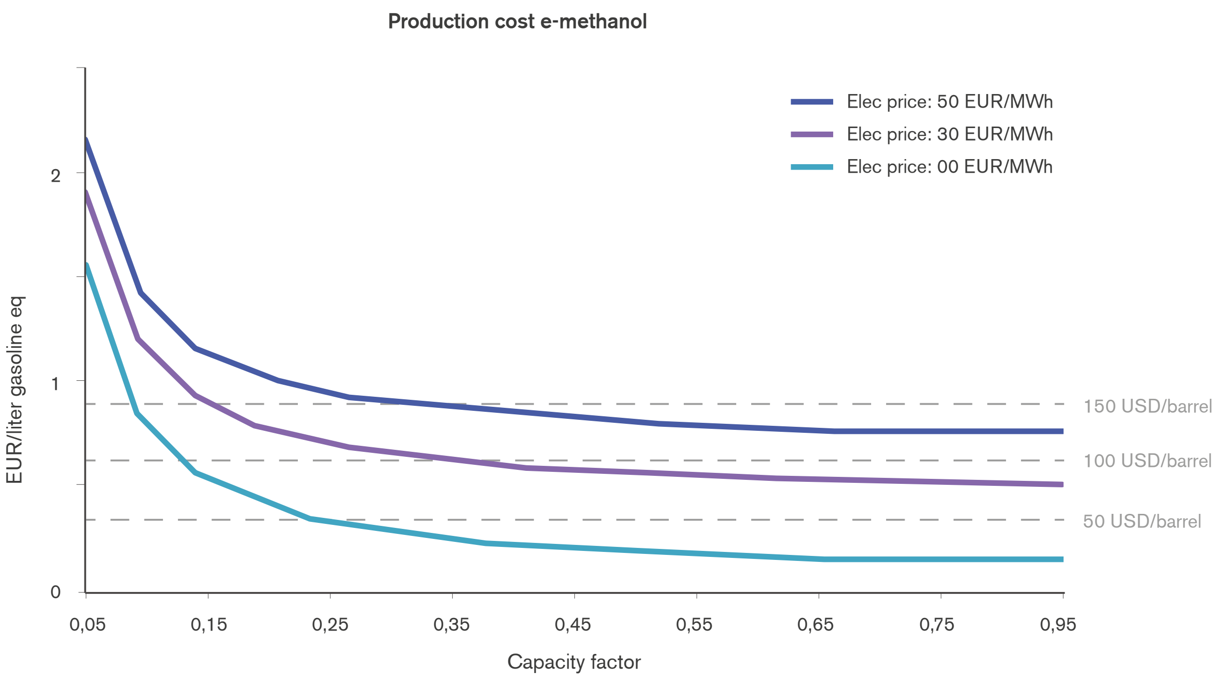

Figure 12.4 Production cost of electrofuels in the form of methanol when assuming that CO_2 is available at 7 EUR/ton, and that electrolysers, with 80% conversion efficiency, are available at 400 EUR/kW (with stack replacements every 7th year). The dotted horizontal lines show the production cost of gasoline, at a crude oil price of 50, 100 and 150 USD/barrel.

With an oil price of 100 USD/barrel and electricity available free of charge, the production of e-methanol is profitable at a capacity factor of 0.15 or higher, which corresponds to a situation that the electrolyser runs at full capacity 15% of the year on excess electricity (and without producing anything 85% of the year). If the electricity price is increased to 30 EUR/MWh, the e-methanol will be profitable if the production process is running, at full capacity, 45% of the year or more. E-methanol will however not be profitable at an electricity price of 50 EUR/MWh and an oil price of 100 USD/barrel or lower. At an oil price of 150 USD/barrel, production of e-methanol can be profitable compared to gasoline for all three electricity price scenarios at relatively low capacity factors, 10%, 17% and 40%, respectively. The cost is more sensitive to the electricity price than to the capacity factor; there is a large increase in cost only at very low capacity factors. This makes the technology suitable for electricity storage.

When the production cost of an electrofuel is lower than the gasoline production cost, the difference indicates the amount that can be paid for CO_2. The availability of CO_2 at low cost will be limited and if one wants to use captured CO_2, e.g. from flue gases, the cost of CO_2 will be higher (see Table 12.1). In this case, a higher oil price or a carbon tax on fossil fuels (see below) is needed to make electrofuels competitive with gasoline. Alternatively, very high capacity factors are required, indicating that the technology will not be a cost-effective option to store excess electricity. Capturing CO_2 from air or seawater will require a very high oil price or carbon tax before they can become profitable (Table 12.1).

A cost for emitting CO_2, for instance, in the form of a carbon tax, will increase the price of gasoline. A carbon tax of 100 EUR/ton CO_2 corresponds to 0.25 EUR/litre of gasoline. Such a tax would increase the competitiveness of electrofuels based on a renewable CO_2 source. When the CO_2 comes from a fossil source, the electrofuel would also have to pay for the emission. The cost would be roughly the same as for gasoline per litre gasoline equivalent, varying slightly with the carbon content per energy unit of the electrofuel and the carbon efficiency of the Sabatier reactor. However, the electrofuel could get credits for recycling CO_2 and thus benefit from a reduced carbon emission penalty. For the CO_2 supplier and the electrofuel producer taken together the net change in emission penalty costs should be zero. How costs and revenues are distributed between the electrofuel producer and the CO_2 supplier ultimately depends on the negotiating power of the parties. The net effect of a CO_2 emission penalty on the competitiveness of electrofuels is therefore not clear, especially as a cost for CO_2 emissions probably also will affect the electricity market.

Costs for CO_2 emissions can possibly be mitigated by Carbon Capture and Storage (CCS). The CO_2 supplier may then have a cheaper alternative to pay for emitting CO_2. This will be unfavourable for the electrofuel producer in a bid for the CO_2.

FUTURE CARBON MANAGEMENT: RECYCLING OR TERMINAL STORAGE OF CO_2

Apart from the economic aspect, one may discuss if it is preferable from a climate change perspective to store captured CO_2 underground or recycle the CO_2 into electrofuels.

From one perspective it is preferable to capture and store CO_2 underground, using CCS technology, and not convert CO_2 into a fuel that after combustion will be released to the atmosphere. If the CO_2 has been captured from burning fossil fuels, CCS will avoid increased CO_2 concentration; if the CO_2 is captured from burning biomass (or from air), CCS will decrease the CO_2 concentration. Today, however, there are several obstacles that have to be overcome before CCS could be available at a large scale, including public acceptance.

If even if CCS is available, should CO_2 always be pumped underground? An argument for converting CO_2 into electrofuels, instead of using CCS, has to do with the lack of long-term fuel options in the transportation sector. If no other major long-term alternative transportation fuels are available or technically possible, e.g. if bioenergy has been expanded to its maximum and batteries as well as fuel cells face difficulties with up-scaling, maybe only synthetic carbon based fuels, electrofuels, remain as an alternative to oil or coal based fuels. Electrofuels produced from non-fossil CO_2 with the help of renewable electricity has the potential to be a large-scale fuel option in a world with ambitious climate targets.

Finally, there might be other advantages of recycling CO_2 into electrofuels and using it instead of producing gasoline and diesel from fossil sources including (i) rural development (if electrofuel production is placed outside cities), (ii) energy security, i.e. less dependency on imported oil, and (iii) reduced environmental impact, e.g., from avoiding the extraction and transportation of oil.

CONCLUSIONS

We conclude that electrofuels for transport is an interesting option of utilising excess electricity, although further research is needed to better understand the potential. We have shown that if the electricity price is not higher than 30 EUR/MWh, and the oil price is not lower than 100 USD/barrel, e-methanol could be profitable if the production process is running at full capacity at least 45% of the year. E-methanol might also be profitable at an electricity price of 50 EUR/MWh if there is a carbon tax on gasoline. One important finding is that the technology is suitable for electricity storage since the production cost of electrofuels is more sensitive to the electricity price than to the amount of hours per year that the production runs at full capacity. Production costs increase significantly only when the process runs less than approximately 15% of the year. Nevertheless, to increase competitiveness, improvements of electrolysers are required, in terms of production cost, conversion efficiency and response time.

The development of an electrofuel production industry may also be determined by other factors apart from the production cost. Electrofuels are, for example, not likely to enter the market as a storage option of excess electricity if alternative low cost electricity storage technologies or other low-emitting alternative transport fuels are developed and produced on a large scale at low cost. Finally, with widespread deployment of CCS, CO_2 might be stored, instead of recycled into electrofuels.

13

THE RESPONSE OF INCUMBENT UTILITIES TO THE CHALLENGE OF RENEWABLE ENERGY

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INTRODUCTION

Renewable energy sources such as biomass, wind and solar power are relatively new means of generating electricity. Until recently, electricity was typically dominated by fossil fuels (coal, gas and oil), large-scale hydro and nuclear power in centralised systems of very large, GW-scale generation units. In contrast, new renewable power is typically built in smaller units and can attract investors outside the traditional circle of utilities and industrial self-generators.[1] Whilst renewables rely heavily on public funding to support their further development and deployment, they are becoming more competitive with traditional electricity generation technologies and can seriously affect their profitability, even their survival.[2] Together these factors mean that incumbent utilities (i.e. major companies that dominate conventional electricity production) have been forced to respond to something we refer to as the 'renewable challenge'.

Since the 1990s, when many European electricity markets were 'liberalised', there has been a trend towards further market concentration. This means that some incumbents are now among the most highly capitalised companies in the world.[3] Prior to liberalisation, many European utilities had close links to the state via public ownership and via sub-national or national monopolies. Utilities were seen as a key

1 Large-scale, centralised concepts such as offshore wind or DESERTEC (solar power) do exist, but most renewable installations are on a smaller scale.
2 Rogol, M. (2011) Explosive Growth, Austin (see Chapter 2)
3 Thomas, S. (2003) The seven brothers. *Energy Policy* 31, pp. 393-403.

infrastructure industry and offered career opportunities to former political leaders and bureaucrats. Hence one would expect that utilities could face the renewable challenge from a position of strength. Surprisingly this has not always been the case. Incumbents in Germany and Sweden – the two countries discussed here – demonstrate a wide range of responses to the renewables challenge.

In this chapter we analyse utilities' responses to the renewable challenge using the reactive-defensive-accommodative-proactive scale as popularised by research on Corporate Social Responsibility.[4] By responses, we refer primarily to incumbents' 'nonmarket' strategies for dealing with renewables. Generally speaking, nonmarket strategies are typically those that seek to influence "the social, political, and legal arrangements that structure interactions outside of, although in conjunction with, markets and private agreements".[5] Since public policy is a major determinant of market opportunities related to renewable energy, we focus particularly on incumbents' attempts to influence renewable energy policies. However, in some instances we describe how incumbents have sought to influence renewables through court cases (legal arrangements) and the media (social arrangements). We trace incumbents' nonmarket strategies in Germany and Sweden through time to show that responses to the renewable challenge vary according to different social and political contexts.

PATTERNS OF RESPONSES

We apply the reactive-defensive-accommodative-proactive (RDAP) scale to examine how incumbent utilities respond to renewable energy developments. The scale is commonly used to examine companies' social responsibility (see Figure 13.1), and is a means of analysing corporate behaviour. Here we characterise utilities that are *supportive* of renewable energy developments as *proactive*. In contrast, utilities that *oppose* renewable energy developments are *reactive*, in that they attempt to block or limit renewable energy policies, for instance, via non-market strategies.

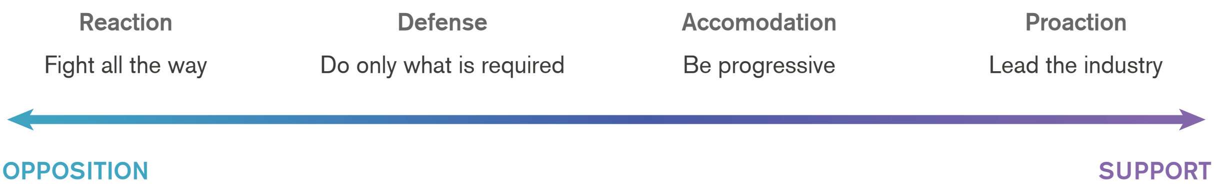

Figure 13.1 The RDAP scale for corporate social responsibility. Adapted from Carroll (1979).

In the *proactive* mode, one would expect incumbents to actively participate in policymaking for new renewable technologies. Incumbents can do this by supporting policy developments and by providing key inputs to policy design. They can also encourage renewable technologies and new business models. As part of a proactive approach, incumbents can form alliances with powerful actors such as political parties, energy intensive industries, and labour unions; foster direct contacts to ministries and MPs; and seek to positively influence public opinion via media and other channels.

4 Carroll, A.B. (1979). A Three-Dimensional Conceptual Model of Corporate Performance. *The Academy of Management Review*, Vol. 4, No. 4, pp. 497-505

5 Baron, D.P. (2003). Business and its environment. Upper Saddle River, NJ: Prentice Hall.

We would expect incumbents to be *accommodative* if they are satisfied with existing public policies, or otherwise if attempts at proactive influence did not achieve their primary goals. Accommodative incumbents may also see new renewables as an opportunity for their own business and thus accept rather than oppose the adoption of renewables among actors outside the utility sector.

In the *defensive* mode, incumbents typically aim to protect their own turf by making things difficult for challengers. For example, incumbents may demand complicated and unfavourable contracts from generators; delay the connection of renewable generation facilities via bureaucratic or 'invented' technical problems; make grid access difficult or very expensive; delay payments to generators or question their own obligations; charge excessive balancing costs; withhold merit order savings by new renewables from consumers; and so on.

Incumbents are likely to resort to the *reactive* mode if they did not achieve their regulatory policy goals, or if they feel sufficiently threatened by new market entrants. In such situations incumbents may take strong, hostile action by questioning the legal basis of the policy to which they are averse; by pressuring governments to modify legislation or decrees in order to slow down renewables deployment or to make it less profitable; by discrediting new renewables as backwards, messing up the landscape, or overly expensive; or by discrediting the particular regulation as a risk to industrial competitiveness and to the market economy.

The choice of these modes partly depends on how individual incumbents respond to the opportunity structure (political, technical, economic, natural resources, public acceptance etc.) they are confronted with. Incumbents' choices will be guided by their profit orientation, but also by different views of the profit potential of new renewables given the business model of the incumbent concerned.

INCUMBENTS' RESPONSES TO THE RENEWABLE CHALLENGE IN SWEDEN

In Sweden, three multinational energy companies produce around 90% of the country's electricity (Vattenfall, E.On and Fortum). Whilst these companies currently dominate the electricity market, municipal energy companies have existed in most Swedish towns and cities for a long time. These smaller utilities are primarily responsible for the provision of district heating, but around 35 municipal companies also produce electricity. Hundreds of landowners also produce electricity in Sweden, though on a much smaller scale. Hence the term 'incumbent utilities' refers to the three main electricity producers together with municipal energy companies that produce both electricity and district heating.

Sweden has a long tradition of hydroelectric power, owing to the fact that the country has a huge resource endowment in the form of large rivers and lakes. The first hydropower plant was built in 1906 and nearly half of the electricity produced in Sweden today comes from hydropower. However, the current debate on renewable electricity has roots in the 1970s, when the oil crises brought about a major reorientation of Swedish energy policy. In order to reduce dependency on imported oil, the government financed research in renewable technologies and energy saving programmes[6] and stepped up the deployment of nuclear power. The major utilities were *accommodative* of these measures, despite the fact that energy savings could potentially reduce revenues. One reason for this is that reducing oil dependency could potentially strengthen major utilities given that municipal companies were heavily reliant on oil. The other reason is that the most significant response to the oil crises was the construction of 12 Swedish nuclear power plants from 1972-1985 – a move that was supported by the major utilities. Despite the fact that renewables offered a potential alternative to oil, Sweden experienced little growth in renewable capacity in the 1970s (see Figure 13.2).

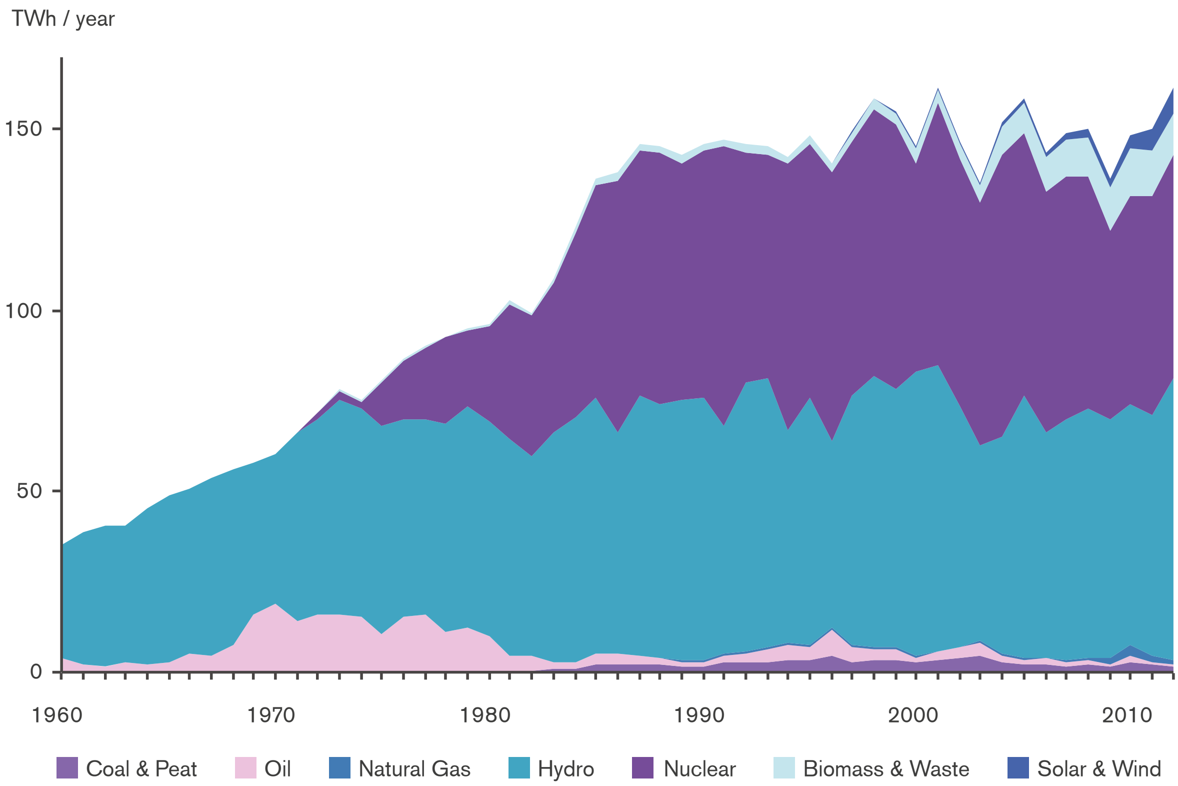

Figure 13.2 Swedish electricity generation 1971-2012. Sources: Data for 1960-2011 from IEA (2014), 2012 adapted from the Swedish Energy Agency (2014).

Alongside its expansion, nuclear power became a politicised issue, and in 1980 it was decided via a national referendum that nuclear power plants should be phased out in Sweden by the end of their operational lives (i.e. 2010). This gave a renewed impetus to the possibility of growth in renewables. Other environmental issues (e.g. acid rain, the ozone problem, climate change) climbed the Swedish political agenda towards the end of the 1980s. Hence in 1991, the government introduced a new long-term energy policy that sought to reaffirm the nuclear phase-out; protect unexploited rivers; and tackle climate change.[7] As part of these changes, the Swedish government sought a unilateral approach on climate change via a carbon tax. In addition to the CO_2 tax, the 1991 energy bill established a new

6 Nilsson, L.J. et al. (2004). Seeing the Wood for the Trees: 25 years of Renewable Energy Policy in Sweden. Energy for *Sustainable Development*, 8, 67-81. Åstrand, K. and Neij, L. (2006). An Assessment of Governmental Wind Power Programmes in Sweden in Sweden Power Programme. Energy *Policy*, 34, 277–296.

7 Nohrstedt, D. (2008). The Politics of Crisis Policymaking: Chernobyl and Swedish Nuclear Energy Policy. *The Policy Studies Journal*, 36, 257-278.

energy efficiency programme alongside further investments in renewable energy technology.[8] The CO_2 tax did not favour wind power, however, and piecemeal subsidisation policies made investments risky.[9] Major utilities were *defensive* towards the CO_2 tax (by opposing it, together with export-oriented energy intensive industries) but in the end had to settle for tax exemptions. Moreover, utilities were opposed to Sweden's unilateral approach to climate change and were *reactive* towards a government attempt to double taxation levels. As part of their reactive strategy, incumbents questioned the validity of climate science and emphasised risks to Swedish industrial competitiveness.

In the early 1990s, Sweden suffered a major economic crisis that resulted in recession. The Swedish government responded by initiating a range of neoliberal market reforms and became a member of the EC as part of a new Swedish growth strategy.[10] The Swedish energy industry linked deregulation to European proposals to harmonise European energy markets. The latter were supported by large utilities such as Vattenfall, given the possibility of expanding into the German electricity market. However, smaller utilities raised concerns that power companies which are forced to compete on price are likely to invest in the cheapest energy sources, with negative effects for the environment, resource use and energy security. At this point the dominant view within the energy industry was that there was a need for long-term, coherent and politically stable policy instruments that would ensure that renewables such as wind turbines could compete with fossil fuels. In other words, incumbents were, together with other electricity producers, *proactive* as regards the introduction of renewable energy policies.

Towards the end of the 1990s, the Swedish government took up an initiative from the European Commission and proposed that an electricity certificate scheme (ECS) replace subsidies for renewables. At this stage incumbents restated their support for renewables and nicknamed the ECS the 'green certificate system'. In the consultation phase that preceded the establishment of the ECS, only one stakeholder group opposed the scheme as part of a *reactive* strategy. The Swedish association of small energy producers (SERO) argued instead for a feed-in tariff, a stance they maintained deep into the next decade. SERO was concerned that small electricity producers would not be able to compete with large utilities in the context of a quota-certificate system, due to their lack of financial capital.

Around 2006, climate change became a salient energy policy issue. During this period, the Swedish government sought to re-establish its unilateral approach to tackling climate change, embodied in ambitious emission reduction targets and further growth in renewables.[11] The EU emission-trading scheme was implemented in Sweden as part of this approach, which was met with opposition from large utilities and energy intensive industry. Together these industries pursued a *defensive* strategy and argued that climate and energy policies should create a level playing field for industries exposed to international competition. The government

8 Nilsson *et al.* (2004). Åstrand and Neij (2006).

9 Åstrand and Neij (2006). Wang, Y. (2006). Renewable Electricity in Sweden: An Analysis of Policy and Regulations. *Energy Policy*, 34, 1209–1220.

10 Nordhaus, W.D. (1997). The Swedish Nuclear Dilemma: Energy and the Environment. Resources for the Future, Washington.

11 Sarasini, S. (2009). Constituting Leadership via Policy: Sweden as a Pioneer of Climate Change Mitigation. *Mitigation and Adaptation Strategies for Global Change*, 14, pp. 635-653.

responded by providing further exemptions, this time by relaxing allocation criteria for emission permits to energy intensive industries.

The three multinational energy companies that operate in Sweden have on other occasions sought to hamper the government's unilateral approach. Particularly Vattenfall, whose portfolio includes coal-fired power in Germany and Poland, forced *Svensk Energi* (the main industry association for the Swedish energy industry) to be more liberal in their stance towards ETS permit allocations. Vattenfall also launched a lobby coalition called '3C' prior to the Copenhagen climate summit that advocated a global climate treaty with emission trading as the main instrument. In doing so, Vattenfall sought to: 1) ensure a level playing field between electricity producers and 2) allay fears that European energy intensive manufacturers may lose out to competition from their Asian or North American counterparts with access to cheaper energy. Whilst the 3C initiative is part of a proactive climate policy strategy, Vattenfall wanted to secure its international customer base (i.e. industrial customers in Sweden and other European countries) in light of the EU's unilateral approach to climate mitigation.

In spite of industry opposition to Sweden's unilateral approach, the electricity industry has for the most part supported the two main policy instruments that currently promote investments in renewable electricity production. The main reason for this is that the combination of the EU ETS and the Swedish ECS has resulted in windfall profits for most energy companies, who are able to take advantage of the fact that around 90% of Swedish electricity is produced from nuclear and hydropower. Increased revenues are mainly the result of price-setting mechanisms in the context of Nordpool (the Nordic electricity market). Particularly the ETS allows Swedish electricity producers to charge the additional costs of marginal fossil fuel production onto consumers, which means that electricity from hydropower (which is typically much cheaper than coal-fired power) is sold at a higher rate than if the ETS did not exist.

One of the main impacts of the ECS has been growth in wind power, from 0.9 TWh in 2004 to 7 TWh in 2012. Whilst this statistic could in theory placate renewable suppliers, small electricity producers have continued to advocate the introduction of a feed-in tariff, albeit as part of a modified political strategy. Having realised that the certificate scheme is here to stay, SERO have instead begun to argue proactively for a parallel FIT system that complements the ECS. Their main argument is that the ECS precludes smaller electricity producers, who struggle to raise the capital required to invest in wind power – especially since the financial crisis. However SERO is still defensive as regards the ECS, having opposed its recent expansion to include Norway. SERO fears that Norway will attract more renewable investments than Sweden given higher potentials for wind power. In doing so, SERO sought the support of the Swedish Wind Power Association and has also established ties with the European Wind Energy Association (EWEA) and the European Renewable Energy Federation (EREF).[12] One reason for this is that smaller energy producers feel ostracised from Swedish policy-making, which

12 Sarasini, S (2013). Institutional work and climate change: Corporate political action in the Swedish electricity industry. *Energy Policy*, 56, pp. 480-489.

is typically performed in a corporatist fashion and led by the agencies of the state in a manner that benefits established industrial actors.[13]

INCUMBENTS' RESPONSES TO THE RENEWABLE CHALLENGE IN GERMANY

By comparison, the German incumbent response to the renewable challenge is far more antagonistic than its Swedish counterpart. There are four big utilities in Germany today (RWE, E.on, EnBW and Vattenfall), down from about a dozen before (incomplete) liberalisation in the late 1990s. They generate electricity mostly on the basis of soft and hard coal, nuclear and gas (in this order) and have a very small share in renewables generation (Figure 13.3). In the energy crisis of the 1970s, the government favoured expanding nuclear and coal generation, also adding modest R&D for renewables. Nuclear and coal however soon became the target of a powerful movement for *Energiewende* (energy transformation towards renewables and efficiency). This social movement held strong anti-nuclear views (majoritarian after Chernobyl 1986) and also opposed coal power – first for its SO_2 emissions, later mostly for CO_2.

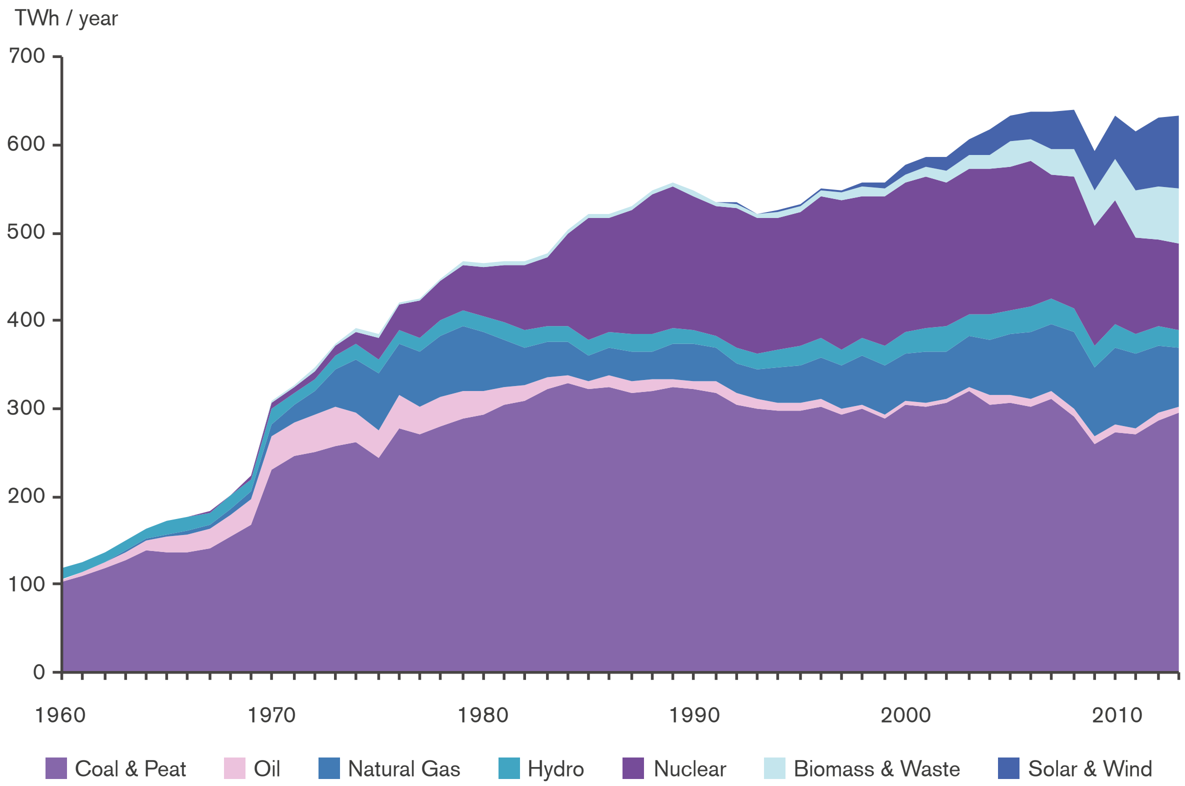

Figure 13.3 German electricity generation 1960-2013. Sources: Data for 1960-2011 from IEA (2014), 2012-2013 adapted from AGEB (2014).

This movement was taken up by parliament (against the preferences of the government and the incumbents) which in 1990 passed a law on a feed-in tariff to support market creation for non-utility, decentralised renewables installations. Ten years later, a Social Democratic-Green government adopted the Renewable Energy Act (EEG – *Erneuerbare Energien Gesetz*) as well as a nuclear phase-out

13 Uba, K. (2010). Who Formulates Renewable-Energy Policy? A Swedish Example. *Energy Policy*, 38, pp. 6674–6683.

law. The former provided for the transition to renewable electricity (but without a time horizon yet) by granting guaranteed twenty-year, highly differentiated tariffs and priority access to renewables. The scope of this law was further expanded in 2004 and 2008 and resulted in the steep growth of wind, biomass and PV power through 2012. In 2013, PV growth was more than halved.

From the beginning, the incumbents had been sceptical or outright hostile towards renewables. Small installations did not fit their centralised paradigm or their business culture. In the absence of sympathy from the government (except for some measures in favour of coal), they resorted to both defensive and reactive approaches. They challenged feed-in tariffs in various court venues; tried to replace them with a quota-cum-certificates system;[14] harassed generators; and tried to turn public opinion against wind and solar. For a long time though these efforts were unsuccessful; even the Conservatives came to support EEG after the 2005 election.

Things changed only in 2009 with a new Conservative-Liberal coalition, which remained in place until 2013. Back in 2000, these two parties had opposed the nuclear phase-out.[15] Now they decided to postpone it by about a decade so that cheap nuclear power could form a bridge to the age when renewables would be affordable and market competitive. This postponement was barely adopted when the Fukushima accident took place, leading to a reversal of the government position. Now it proposed to accelerate *Energiewende*, while at the same time making it affordable by supposedly subjecting it to market discipline.

At this time the incumbents were urging a slowdown of renewables deployment. This deployment had become quite rapid and cut into their markets and their profits, partly as an effect of the merit order system (based on marginal costs of production) prioritising renewable electricity (see also Chapter 11 and 15). This eliminated the more expensive forms of fossil generation (i.e. oil, gas and some hard coal plants) and meant steadily falling prices on the electricity exchange from 2008 onwards. PV had the most devastating impact on incumbents' profits since it reduced demand for conventional generation at peak hours and peak prices. It grew by 22.5 GWp in just three years, 2010-2012, to reach about 35 GWp in 2013. Within a few years, profits and stock values of the incumbent utilities plummeted;[16] the outlook for the future seemed dim as the Renewable Energy Act of 2000 limited conventional generation to providing the 'residual load' that renewables could not yet meet.

The Conservative-Liberal government was willing to accommodate incumbents' demand for slowing down renewables, claiming that the latter's cost to consumers had become unacceptable while refusing to deal with the underlying problem of the EEG surcharge (see Chapter 15). Beginning in 2010, the government came

14 Compare the development of the ECS in Sweden. However, German supporters of quotas looked at the UK, not at Sweden. Quota systems are advantageous to incumbents as they tend to keep non-incumbents away, produce sizeable windfall profits and limit deployment overall Lauber, V. (2011). The European Experience with Renewable Energy Support Schemes and Their Adoption: Potential Lessons for Other Countries. *Renewable Energy Law and Policy Review*, 2:2, 121-133..

15 Even the incumbents were not eager for new nuclear build given its controversial nature in Germany.

16 The Economist (2013). European utilities: How to lose half a trillion euros. Europe's electricity providers face an existential threat, 13 Oct.

up with a variety of initiatives to impose limits to deployment of renewables which it is true had exceeded expectations,[17] first by extending the lifetime of nuclear; in 2012-13 it attempted to introduce caps on deployment or on support. The more radical attempts were stopped by opposition from the regions (*Länder*). In late 2013 however, a similar approach was incorporated into the coalition agreement for the new Conservative-Social Democratic government.[18] First legislative drafts propose to contain growth of renewable electricity by a corridor that replaced former minimum targets that were regularly overshot, and to abolish feed-in tariffs within a few years in favour of market premiums set via bidding systems.

Incumbents also sought modifications of the electricity market framework to protect conventional generation from the advance of renewables, arguing that the declining profits of coal generation after 2008 endangered the security of electricity supply as it would inevitably lead to shutting down coal plants needed to guarantee against shortfalls of intermittent renewables. Yet a new wave of coal plants is coming online – one of the biggest expansions since the days of post-World War II reconstruction.[19] Despite this abundant supply of conventional generation the incumbents now demanded capacity payments to improve the economics of fossil standby plants. This solution was resisted by the Conservative-Liberal government but met with more sympathy from the Conservative-Social Democratic government that took office in 2013. In that year, the incumbents also proposed a new support system for renewables based on market premiums (to replace the EEG's feed-in tariffs) which would remove incentives to operate wind and solar plants during periods of oversupply resulting from the inflexibility of conventional plants (nuclear, soft coal, to some extent hard coal – see also Chapter 11).[20] First legislative initiatives in early 2014 incorporated those proposals.

Recently, incumbents have been moving hesitatingly into the renewables business themselves. For a long time they had fostered the dream of gigawatt-scale wind and solar farms in North Africa to transmit electricity to Europe (DERSERTEC) as part of their future business activity. With cheaper solar panels and the investment insecurity that followed the Arab spring, this dream has suffered a severe setback. Offshore wind in the North and Baltic seas is a European alternative but slow in coming (see Chapter 15 and 16); German incumbents prefer to build offshore plants in more profitable settings abroad. But in 2008 and again in 2013, at least some of the incumbents have indicated that they see a future for themselves in renewable energy and accept the progressive decline of conventional generation, as recently stated by RWE's chief executive.[21] Even solar PV seems to be on the incumbent agenda now, both in terms of big solar farms and rooftops.[22] But then the alternative – a radical shrinkage of incumbents' German operations – does not seem unlikely either.[23]

17 In its 2010 National Renewable Energy Action Plan to the EU (2010), Germany proposed a target for RES-E of 38.6%, slightly more than 10% higher than the 35% set in Energiekonzept 2010 and the 30% of EEG 2008.
18 The Social Democratic Party contains a 'coal fraction' sympathetic to coal power which came to the fore recently.
19 International Energy Agency IEA (2013) Energy Policy of IEA Countries – Germany, 2013 Review. Paris.
20 BDEW (2013) German Association of Energy and Water Industries. Proposals for a fundamental reform of the German Renewable Energy Source Act. Position paper, Berlin, 18 Sept.
21 Terium, P. (2013) RWE-Chef Terium plant radikalen Strategieschwenk. Handelsblatt, 29 October, accessed 23 Nov 2013.
22 IEA (2013) Trends in Photovoltaic Applications, Paris.
23 Becker, P. (2011) Aufstieg und Krise der deutschen Stromkonzerne. Ponte Press.

CONCLUSIONS

Our analysis shows that incumbents have responded very differently to the renewable challenge in Sweden and Germany. As noted previously, the German case is far more antagonistic than its Swedish counterpart. These differences can be attributed in part to natural resource endowments. Germany, for instance, is a domestic producer of soft coal; has fewer sources of hydropower and biomass than Sweden; and there is little storage for solar and wind power, which aggravates the problem of intermittency. In contrast, Sweden has large potentials for wind power and biomass; a large proportion of Swedish electricity is produced from hydropower; and both biomass and hydro are largely regular or dispatchable. The composition of the electricity system in terms of installed technologies and fuels is thus also an important determinant of the incumbent response to renewables.

Another factor that differentiates the Swedish and German cases is the political, or energy policy-making system. We characterise the Swedish political system as a relatively closed corporatist system dominated by big industry, trade unions and the agencies of the state. In contrast the German system, despite also being largely corporatist, is more open and subject to influence from powerful social movements, which led to the introduction of a feed-in tariff and the subsequent deployment of renewable generation overwhelmingly by non-utility investors who despite lower rates of profitability are more committed to deployment than incumbents.

This difference in the political subsystem makes the German and Swedish cases in a sense mirror opposites in terms of regulation. In Sweden, incumbents have proactively influenced renewable energy policymaking, with the result that the existing quota system is financially beneficial for them. Feeling alienated, smaller electricity producers have pursued a reactive strategy, albeit with little success. In contrast, German incumbents were not able to impose their policy preferences, opposed the feed-in tariff throughout and largely missed the boat on deployment. Their reactive approach has included various nonmarket tactics that have sought at first to raise practical hurdles for private investors, and later to alter the political, legal, social and market arrangements for renewables in order to inhibit rapid deployment. When deployment had acquired substantial momentum, they shifted their focus to slowing it down via unfriendly regulation. Only very late in the game did they consider moving into the sector on their own.

Taken together, our cases suggest that incumbents respond according to their perceived financial interests, and their responses to the renewable challenge vary according to how they think they can maintain their market positions, including their profit expectations. Of course, these views reflect the bounded rationality of very large, centralised and cumbersome organisations. On the whole, their profit orientation was too short-term to envision active participation in the early phase of renewables development, whose then small installations seemed anti-modern and were easily identified with anti-nuclear positions that were anathema to the utilities in those days. In addition the latter needed to protect existing generation at times of slow growth of electricity consumption. In Sweden, the utilities used their good access to politics to secure a quota-and-certificate system which selected technologies that were profitable and easily integrated. In Germany, utility refusal of a strong demand from society meant that they were eventually bypassed in a way that proved quite disruptive. The current government now appears determined to come to the help at the cost of slowing down the energy transition.

14

ON THE GERMAN AND EU COST DISCOURSE – IS LARGE-SCALE RENEWABLE POWER SUPPLY "UNAFFORDABLE"?

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INTRODUCTION

Germany's Renewable Energy Act (EEG), adopted in 2000, played a decisive role for the remarkable development and deployment of renewable energy technologies in Germany between 2000 and 2012, and of a capital goods industry able to fulfil that task. It was controversial with some actors from the beginning, essentially with those who opposed its philosophy of an active government's role in the far-reaching transformation of the electricity sector, either for ideological reasons (because they would leave things to the "market") or for reasons of self interest (fossil fuel incumbents threatened by the advance of renewables). However, only since about 2009 has the EEG come in for radical attack from the government. The chief argument behind its discourse is that the transformation of the energy system (*Energiewende* in German) has become too expensive, threatens to sap Germany's economic strength and, therefore, needs to be slowed down and made "affordable". Our goal is to critically analyse this argument by showing that the cost calculations used are highly political in what they take into account and what they neglect, even if they may reach their aim of curtailing *Energiewende*.

In 2000, the EEG replaced the 1991 Feed-in-Law. It introduced fixed and technology-specific cost covering payments per kWh for 20 years; automatically decreasing payments for new investments; unlimited obligation by grid operators to buy all tendered electricity from renewable sources and priority dispatch. EEG led to i) growth of renewable power production from 29 TWh in 1999 to 144 TWh in 2012, ii) 1.3 million owners of decentralised power plants in 2012 and iii) a German industry employing over 350 000 in 2011.[1] EEG is an unusual and, in some important ways, successful policy which draws its legitimacy from a long history of concern over the risks of nuclear power, forest dieback and climate change. The legitimacy was continuously nurtured by a strong social movement which focused on the long-term *total impact – and costs* – of energy supply.[2]

The large utilities, the energy intensive industry, the Conservative and Liberal Party leaderships and, on several occasions, the Ministry of Economic Affairs attempted, however, to undermine or stop even the modest 1991 Feed-in law and vigorously fought the EEG, both its initial adoption and its subsequent extension in 2004. A temporary pragmatic consensus between Conservatives and Social Democrats ended when a Conservative-Liberal coalition came to power in 2009, arguing the need to restrict the "excessive" deployment of renewables in order to make *Energiewende "affordable".* EU energy commissioner Oettinger fuelled the critique of the EEG as did some academics who suggested that the EEG surcharge levied on consumers to finance investment in renewables constitutes a large "burden" on electricity consumers. A clear shift in the discourse took place from a focus on long-term total costs of energy supply to short-term consumer costs. In early 2013, the Minister of the Environment, Peter Altmaier responded by submitting legislation to stop the increase in electricity bills supposedly caused by the EEG and Liberal members of the government even suggested discarding the EEG entirely.[3]

The German debate on "affordability" spilled over to many EU countries, raising legitimacy questions over this form of support and associated technologies. For instance, it is present in the European Commission's Green Paper which discusses policy for 2030 and where it is argued that a central consideration for future policies is "*concerns of households about the affordability of energy and of businesses with respect to competitiveness*".[4] Another example is the head of the Committee on Industry in the Swedish Parliament, M. Odell, who explicitly links the German price of electricity (for non-privileged customers) of about 28 eurocents to wind power policy.[5] Yet, a simple calculation reveals that the impact was at most in the order of 0.3 eurocents/kWh in 2012.[6]

1 AGEB (2013), Bruttostromerzeugung in Deutschland von 1990 bis 2013 nach Energieträgern, Arbeitsgemeinschaft Energiebilanzen; FME (2012), Development of renewable energy sources in Germany 2011, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

2 Jacobsson, S. and Lauber, V. (2006), The politics and policy of energy system transformation: explaining the German diffusion of renewable energy technology, *Energy Policy*, 34 (3); Dewald, U. and Truffer, B. (2012), The local sources of market formation: explaining regional growth differentials in German photovoltaic market, *European Planning Studies*, 397-420.

3 Frondel, M. et al. (2010), Economic impacts from the promotion of renewable energy technologies: The German experience, *Energy Policy* 38; Der Spiegel (2013), German Environment Ministry Plans to Cap Subsidies for Renewables, January 29.

4 European Commission (2013), Green Paper. A framework for climate and energy policies, COM (2013)169, Brussels.

5 Odell, M. (2014): Dags att trappa ner stöden till vindkraft, SvD Opinion, January 27.

6 In 2012, wind power supply was 51 TWh and was remunerated by 8.8 eurocents/kWh. The spot price for electricity was 5.4 eurocents/kWh (AGEB, 2013); Kuechler, S. and Meyer, B. (2012), Was Strom wirklich kostet, Forum Ökologisch-Soziale Marktwirtschaft (FÖS), Berlin, September. The extra cost of wind power then equals 1734 million EUR. Dividing with a total electricity consumption of 607 TWh, we come to an added cost of 0.29 eurocents/kWh. This overestimates the added cost as it ignores merit-order effects of wind power (reducing spot market prices) and subsidies for conventional generation (increasing the gap between wind power feed-in tariffs and spot market prices).

Hence, the perhaps most successful regulatory framework for promoting the deployment of renewables, and an associated growth of innovative capital goods industries, was contested from its start. Moreover, it is contested with increasing ferocity at the same time as the International Energy Agency warns about the prospect of towards five degrees global warming.[7]

In this chapter, we reflect on the German cost discourse with special emphasis on the notion of "affordability". We discuss how the discourse (i) misrepresents the impact of the EEG surcharge on consumer costs and (ii) exaggerates the "burden" from renewable electricity by shifting focus from total cost to consumer cost. These two themes involve ascertaining how costs are calculated and therefore what is meant by "cost-efficiency", "subsidy" and "affordability". We then proceed to discuss (iii) inter-generational equity issues arising from our (in)ability to foster the development of new capital goods industries with innovative capabilities. In the final section we identify two complementary explanations of the ferocity of the discourse.

MISREPRESENTING THE EEG SURCHARGE'S IMPACT ON CONSUMER COST

The EEG surcharge is usually discussed as the "extra cost" of renewable electricity supported by EEG payments which is charged to consumers, i.e. the price gap to conventional electricity (fossil or nuclear) as reflected in spot-market prices. It was initially low but rose to 1.2, 3.5 and 5.3 eurocents in 2008, 2011 and 2013, respectively.[8] It would be easy to conclude that there is a growing "burden" on consumers. However, the surcharge is only one element of consumer price – in 2011, it accounted for 14 per cent of household electricity prices,[9] and grew to about 18.5 per cent by 2013. In addition, had the extra costs from EEG installations been allocated evenly across *all* electricity consumers and other distortions been removed, the "burden" from compensating EEG installations in 2013 would have been – according to an analysis widely referred to – 2.3 cents/kWh instead of 5.3 cents.[10] This may well be argued not to be an overly large share of a consumer price of about 28 eurocents.

The discrepancy means that there are other cost components in the surcharge. First, a growing range of industries is largely exempted from the surcharge.[11] In 2013, this industry privilege amounted to 1.3 eurocents/kWh, i.e. this part of the "burden" was shifted from industrial firms to small consumers, mostly households and small business.

7 IEA (2013, p. 9), Redrawing the energy-climate map, World Energy Outlook Special Report, International Energy Agency, Paris.

8 BMU (Bundesministerium für Umwelt) (2012), Erneuerbare Energien in Zahlen.

9 Traber, T., Kemfert, C. and Diekmann, J. (2011), Weekly Report. German Electricity Prices: Only Modest Increase Due to Renewable Energy expected, German Institute for Economic Research, No.6, volume 7, March 16.

10 BEE (2012), BEE-Hintergrund zur EEG-Umlage 2013, Berlin. The cost will increase to 2.54 cents in 2014, (Fraunhofer ISE, 2013, Fig. 15, Aktuelle Fakten zur Photovoltaik in Deutschland, version 12 Sept).

11 Industry includes not only energy-intensive firms facing international competition but also golf courses, newspapers and cheese makers (Der Spiegel, 2012, Germany to Exempt 1 550 Firms From Power Price Surcharge, December 24; Der Spiegel, 2013, European Commission Plans to Probe German Renewable Energy Law, July 15). The initial regulations gave exemptions to firms using more than 10 GWh a year but this was lowered in several steps (Der Spiegel, 2013, European Commission Set to Fight German Energy Subsidies, Spiegel Online, May 29). Exempted industry pays some of the lowest electricity prices in Europe, non-exempted industry one of the highest (IWR, 2013, Strompreis-Kluft spaltet deutsche Industrie, Oct 24). Fraunhofer ISE (2013), Figure 19 reports that 53% of the electricity consumed by industry was associated with payment of a reduced surcharge. Industry uses almost half of all electricity, households about one quarter.

A second factor increasing the surcharge in 2013 is the reduced spot price of electricity due to the merit-order effect (induced by a growing supply of renewable electricity with priority dispatch status), falling coal prices and declining ETS certificate prices.[12] This meant that the gap between the spot price for electricity and the feed-in rates widened, increasing the need for compensation. This effect was estimated by to account for 0.69 cents/kWh in 2013 and would constitute a benefit rather than a "burden" if the reduced spot price led to reduced household consumer costs, which it does not.[13] As it was, this only benefited industrial firms negotiating their own contracts.

Third, another 0.69 cents was due to balance the surcharge account for 2012, i.e. payments decided on in 2011 were not sufficient to cover the year's cost. This constitutes only a temporary increase in the surcharge.

SHIFTING FOCUS FROM TOTAL COST TO CONSUMER PRICE

The shift from total costs to consumer price means that significant cost items are left out of the analysis. The first are external costs which are those that electricity suppliers and users impose on others without paying for the consequences. These costs are real in that they involve damages, e.g. those who suffer from respiratory diseases or are affected by damages to buildings and those who suffer directly from more frequent climate-related draughts and storms. They are also real for those who have to pay for adjustments to various effects of climate change, for example, the costs of avoiding the flooding of coastal cities. The present "affordability" discourse ignores these cost items altogether or considers the EU emission trading scheme as an adequate answer, which at current prices it is not (and which does not cover all types of emissions).

While calculating external costs of electricity generation is fraught with difficulties, the German Federal Environment Agency estimates these to be about 11 and 9 eurocents/kWh for soft and hard coal respectively.[14] These estimates are used by Kuechler and Meyer who add a second ignored cost item, subsidies channelled through the state budget, to estimate the total costs of electricity.[15] Table 14.1 contains their cost estimates (column 1), volume of electricity supplied by various technologies (column 2) and total costs associated with each technology in 2012.

A weighted average cost per kWh is then calculated for the present stock of onshore wind, hydro and PV as well as for hard and soft coal generation facilities – coal being the dominant source of electricity in Germany. In the table, we use the term legacy cost for renewables since it averages payments to earlier installations, with higher tariffs, and those to new installations, with lower tariffs.

12 From a peak at 6.8 Ct/kWh in 2009, spot market prices fell about 28% to 4.8 Ct in 2013 (Fraunhofer ISE 2013, 15).

13 BEE (2012). See also Tveten, A., Bolkesjo, T.F., Martinsen, T. and Hvarnes, H. (2013), Solar feed-in tariffs and the merit order effect: A study of the German electricity market, *Energy Policy* 61.This phenomenon (reduced spot prices not being passed on to consumers) is usually attributed to lack of competition among suppliers and the fact that suppliers strongly rely on futures so that price reductions are not reflected immediately; some also perceive a lack of market supervision and abuse of the "basic supply" tariff.

14 UBA (2012), Methodenkonvention 2.0 zur Schätzung von Umweltskosten, Umweltbundesamt, Dessau-Rosslau; UBA (2012a), Schätzung der Umweltkosten in den Bereichen Energie und Verkehr. Umweltbundesamt, Dessau- Rosslau.

15 Kuechler and Meyer (2012, table 8) calculate total costs for coal power by adding three cost components: a) market price of electricity b) subsidies and c) not internalised external costs. As an example, the cost components for hard coal were 5.4, 1.9 and 7.5 eurocents respectively. For renewable energy technologies, they add the feed-in cost to subsidies and not internalised external costs. We are uncertain how much of the hydropower that receives feed-in remuneration.

Table 14.1: An estimate of the weighted average total cost of electricity supply for renewables versus coal in Germany in 2012

Technology	Total cost (cents/kWh)	Electricity supply (TWh/year)	Total costs (billion EUR/year)
Renewables (weighted average legacy cost)	15.4		
Onshore wind	*8.0*	*51*	*4.1*
Hydro	*7.6*	*22*	*1.7*
PV	*36.7*	*26*	*9.5*
Coal (weighted average cost)	15.3		
Hard coal	*14.8*	*116*	*17.2*
Soft coal	*15.6*	*159*	*24.8*

Sources: Kuechler and Meyer (2012, table 8); AGEB (2013)

As Table 14.1 shows, the weighted average cost per kWh of the three renewables is the same as that of coal and the cost of onshore wind and hydro is much below, i.e. these are not subsidised but cost-efficient. Thus, the "burden" of renewables is negligible when total costs are considered. The contrast with analyses failing to include external costs and subsidies is sharp. An example is Frondel et al. (2010, p. 4049):

> "*…utilities are obliged to accept the delivery of power….into their own grid…paying…feed –in tariffs far above their own production costs…even on-shore wind…requires feed-in tariffs that exceed the per kWh cost of conventional electricity by up to 300% to remain competitive*".

As Table 14.1 also shows, the historically very high feed-in rates of PV as *legacy* costs have a large impact on the weighted average cost. These are, however, sunk costs and should not form the basis for decisions on future deployment. Current PV feed-in rates are, indeed, much lower (e.g. 9.5 to 13.7 eurocents in January 2014).[16] As external costs and subsidies are low, *even PV is now becoming competitive with coal in terms of total costs which implies that, henceforth, coal power is the cost-inefficient option*. Moreover, when green-house gases accumulate, the external cost of fossil fuel use will rise.[17]

To conclude, with these German estimates of external costs and subsidies, it is evident that the cost discourse grossly exaggerates the "burden" of renewables and raises strong doubts about arguments referring to "cost-efficiency", "subsidies" and "affordability" when these terms are used in ways that neglect important cost items. Yet, any consumer cost increase puts low-income households under pressure and these have, of course, to be shielded from the cost of transformation.[18]

16 Solarförderverein (2013), http://www.sfv.de/lokal/mails/sj/verguetu/htm

17 UBA (2012a) argues that these may increase from 80 EUR/t to 145 EUR/t in 2030.

18 See for example discussion in IEA (2013a), Energy Policies of IEA Countries, Germany, 2013 Review, International Energy Agency, Paris

SHIFTING FOCUS FROM LONG-TERM BENEFITS TO SHORT-TERM COSTS

The shift in focus from *long-term* benefits, in the form of e.g. avoidance of impacts of climate change[19] to *short-term* costs means that the discourse has come to ignore large inter-generational equity issues. Renewables are a major requirement for the civilised survival of future generations, not just one possible option among others (See Chapter 3 for an appraisal of the potential of renewables to fully replace fossil fuels). If we accept this, there are large inter-generational positive externalities coming from building capital goods industries and developing technologies that will be able to provide a rapidly rising volume of "low-carbon" electricity, at reasonable consumer prices, as other energy sources are phased out in the second quarter of this century.

For this to happen, a short-term focus on costs must be replaced by a long-term view allowing for the decades long time-scale in the development and diffusion of new technologies.[20] In the innovation system literature, efforts have been put into assessing the length and character of the "formative phase" in which the technology is "put on the shelf", i.e. a rudimentary capital goods industry is developed that provides a technology with a reasonable price-performance ratio.[21] This phase often takes a couple of decades and two to three additional decades may be required to increase the capacity of the capital goods sector and deploy the technology (in further improved forms) until the market is saturated.

Onshore wind and PV have gone through the formative phase and can now be deployed on a large scale with total costs lower than coal (Table 14.1). The 1991 feed-in law and EEG greatly contributed to the formation of capital goods industries and the maturation of these two technologies. Another potential large source of low-carbon electricity in Germany is offshore wind power but this innovation system is still in the formative phase (see Chapters 15-16). The annually installed new capacity of offshore wind turbines in Europe increased from 0.9 GW in 2010 to 1.2 GW in 2012 and is estimated to increase to 1.9 GW in 2014. If we are to reach the targets for the EU of 44 GW in 2020[22] and 200-300 GW by 2050,[23] the addition of new power plants needs to grow to almost 10 GW per year in the coming decade and thereafter remain at that level.

19 Additional expected benefits are reduced problematic imports and reduced consumer costs of electricity as renewable technologies come down in price.

20 Grübler, A. (1996), Time for a change: On the patterns of diffusion of innovation. *Daedalus* 125(3); Carlsson, B. and Jacobsson, S. (1997), Variety and Technology Policy - how do technological systems originate and what are the policy conclusions? In Edquist, C. (ed): *Systems of Innovation: Technologies, Institutions and Organizations*, Pinter, London; Jacobsson, S., Bergek, A., Finon, D., Lauber, V., Mitchell, C., Toke, D., Verbruggen, A. (2009), EU renewable energy support policy: Faith or facts? *Energy Policy* 37; Wilson, C. (2012), Up-scaling, formative phases, and learning in the historical diffusion of energy technologies, *Energy Policy* 50.

21 Jacobsson, S. and Bergek, A. (2004), Transforming the energy sector: the evolution of technological systems in renewable energy technology, *Industrial and Corporate Change*, 13 (5); Suurs, R. (2009), Motors of sustainable innovation. Towards a theory on the dynamics of technological innovation systems, Innovation Studies Group, Copernicus Institute, Utrecht University; MacKerron, G. (2011), Renewable energy and innovation policies: European experience, presentation to the International workshop on Innovation policies and structural change in a context of growth and crisis, Rio de Janeiro, September 13-15.

22 This is the current targets of EU member states (Beurskens, L., Hekkenberg, M. and Vethman, P. (2011), Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States. ECN and European Environment Agency. In our scenario, the 2020 goal of 44 GW is reached in 2022.

23 In European Commission (2011), Energy Roadmap 2050: Commission staff working paper, Impact Assessment, SEC (2011) 1565, the average supply of offshore wind power in five decarbonisation scenarios is 818 TWh which is equal to 234 GW installed capacity with a 40% capacity factor.

A northern European supply chain is, indeed, being developed and Germany is integral to this effort, both as a market and a supplier of capital goods and services. Danish and German firms dominate the market and large investments are made in the whole value chain, including harbours, to develop a supply capacity. However, the proposed cap on EEG payments by Minister of the Environment, Peter Altmaier (see above) led to large political uncertainties and made investors hesitant. Ronny Meyer, managing director of industry association WAB, informed that "the market has collapsed" and, in summer 2013, the Cuxhaven harbour, which invests substantially in infrastructure to enable deployment of turbines, sent out a plea to the government to reduce uncertainties.[24] Hence, the discourse focus on short-term consumer costs, and the associated political uncertainties, puts at risk the formation of a supply chain large enough to develop and deploy offshore wind turbines on the required scale, in time and at a reasonable cost.

Offshore wind is just one example of a technology that is far from being "market ready" and in need of support such as the one granted by EEG in the past. Other technologies – more relevant for other countries than Germany – include wave and tidal power and concentrated solar power. For their early availability, and thus for phasing out fossil fuels and – in the European case – for reducing dependence on energy imports, it makes a big difference whether they are only supported by R&D or also by an appropriate level of market creation of the kind achieved by EEG in the past.

The focus on short-term costs obscures the need to form growing protective market spaces to take the technologies through their formative phase and into the growth phase. With the long time-scales involved (and associated learning costs), current investments should not only be judged by their present costs but also by their contribution to reduce future costs of avoiding climate change by enabling the development of a capital goods sector and other parts of the supply chain. An appropriate cost concept should therefore also include long-term benefits from learning, strengthening the economic case of renewables further.[25]

The German Liberals, some economists, the German Council of Economic Experts and the Monopoly Commission maintain, however, a short-term view and argue that a reduction in the "burden" would be achieved by a quota system, such as the Swedish "technology-neutral" system of tradable green certificates in the electricity system for renewables.[26] Unlike the highly differentiated German feed-in system, such a system – unless it provides for technology banding (i.e. granting more certificates for specific technologies, a crude imitation of the differentiation allowed by feed-in tariffs)[27] – provides incentives to invest in only the *currently*

24 (Der Spiegel, 2013b); Handelsblatt (2013), http://www.handelsblatt.com/technologie/das-technologie-update/themen-und-termine/offshore-industrie-buendnis-unterzeichnet-cuxhavener-appell/8693476.html, dated 26 August, accessed 16 Oct 2013.
25 See e.g. Sandén, B. (2005), The economic and institutional rationale of PV subsidies, *Solar Energy*; Sandén, B. and Karlström, M. (2007), Positive and negative feedback in consequential life-cycle assessment, *Journal of Cleaner Production* 15.
26 Frondel et al. (2010); Sachverständigenrat zur Begutachtung der gesamtwirtschaftlichen Entwicklung (2012) Jahresgutachten 2012/13, chapter 7 (III), 279-297, http://www.sachverstaendigenrat-wirtschaft.de/jahresgutachten-2012-2013.html, accessed 31 Oct 2013;Monopoly Commission (2013): Monopoly Commission publishes Special Report on the situation of competition on the energy markets, press release, Bonn, September 5th.
27 Such banding (introduced in the UK Renewables Obligation) also makes a quota system more expensive.

most cost-efficient technologies and may, therefore, appear attractive with today's German cost discourse.[28]

Yet, it does not drive technical change more than incrementally since it does not stimulate the formation of the markets required to induce the build-up of new supply chains until lower-cost technologies have saturated their markets.[29] In response, it is often argued that immature technologies should not be fostered by market formation policies but rather by R&D policy. For instance, Frondel et al., 2010, p. 4055, argue that: " …one should have abstained from strongly subsidizing the market penetration of relatively immature PV technologies. Rather, from an economic perspective, R&D funding should have increased first".

It is, however, only in the much criticised linear model of innovation that the innovation process constitutes a smooth flow down a one-way street,[30] i.e. where research leads to development, development to production and production to market diffusion and where, hence, (academic) R&D is sufficient for driving innovation and cost-reductions.

Of course, R&D is required throughout the life-cycle of a technology, but it has to be supplemented by market formation in order to stimulate the formation of a capital goods sector and induce it to conduct R&D, product development and other measures that drive down cost (e.g. standardisation efforts). Hence, while in the linear model markets materialise after a technology is fully developed, real life technologies co-evolve with markets. The limitation of a pure quota system (without technology banding) is, thus, that it does not contribute much to "putting new technologies on the shelf"[31] through providing the time and markets required for fostering new capital goods industries with innovative capabilities.[32] An extensive use of a quota system would, therefore, mean that we risk failing to provide future generations with the ability to supply carbon-neutral electricity on a large scale with technologies that have gone through decades of improvement.

CONCLUDING DISCUSSION – TOWARDS EXPLAINING THE FEROCITY OF THE DISCOURSE

In sum, the cost discourse is not only extremely weak and misleading but also ferocious. We conclude by pointing to a few contributing explanations to its ferocity, acknowledging that there are more.

28 It should be noted that the German association of electricity incumbents does not think that this system is able to resolve current problems and now supports market premiums (IWR, 2013), Empfehlungen der Monopol-Kommission: Energiewirtschaft lehnt das Quotenmodell ab, 5 Sept. http://www.iwr.de/news.php?id=24478, accessed 28 Oct 2013.

29 Jacobsson et al., 2009; Bergek, A. and Jacobsson, S. (2010): Are Tradable Green Certificates a cost-efficient policy driving technical change or a rent-generating machine? Lessons from Sweden 2003-2008, *Energy Policy*, 38. See also Azar, C. and Sandén, B. (2011), The elusive quest for technology-neutral policies, *Environmental Innovation and Societal Transitions* 1, on the concept of "technology-neutrality".

30 Kline, S. and Rosenberg, N. (1986), An Overview of Innovation, in R. Landau and N. Rosenberg (eds), *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, Washington DC: National Academy Press.

31 Sandén, B. A. and Azar, C. (2005). Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches. Energy Policy, 33:1557-1576.

32 As the diffusion of renewables increases, there is a growing need for additional policies to support e.g. demand-side management (Chapter 10), electric grids (Chapter 9) and energy storage technologies (Chapter 5 and 12). For the latter, the German government has a programme involving 100 million EUR in investment support just for batteries connected to small PV systems. Grid financing also takes place outside of the EEG.

The German discourse is not unique but reflects a broader, partly ideological, debate between those arguing the advantages of industry- or technology-neutral policies[33] and those advocating a more powerful state implementing industry or technology-specific policies. The latter also highlight the capital goods industry as a bridge between policy, market formation and technical change and the long time-scale involved in building such industries.

In the former camp of the German debate, we find those who (i) emphasise high consumer costs of new technologies and not their total costs; (ii) take a short-term view on both costs and required learning periods; (iii) neglect or play down the role of market formation in innovation and cost reduction and (iv) neglect the volume of past development and deployment support to conventional generation which reached hundreds of billions of EUR.

In the latter, we find those who (i) emphasise total costs, including costs for environmental degradation; (ii) take a long-term view on costs and required learning periods and (iii) argue that market formation is central to innovation and cost reduction. To an extent, the ferocity of the debate can be explained by these diametrically opposite views on the nature of large-scale transformation processes and the different roles to be played by the state.

As much of the debate has centred on the cost of PV, it is though important to acknowledge that in 2010-2012, the inordinate cost of new PV installations in Germany (22.5 GW in three years) impacted very strongly on the surcharge (Table 14.1). The problem arose because the price of modules decreased much faster than the feed-in tariff, creating extra profits and drawing new investors – and because no decisive steps were taken in time. But this is a legacy cost item in the surcharge that will not come down even if a quota system is installed today. In a long-term perspective, the central observation is that PV has now become so cheap that the impact of its future deployment on the surcharge will be very modest.

Yet, the divide is also due to genuinely conflicting economic interests of firms. Schumpeter once argued that

> *… in capitalist reality as distinguished from its textbook picture, it is not that kind of competition*[34] *which counts but competition from the new commodity, the new technology, the new source of supply, the new type of organization – competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of existing firms but at their foundations and very lives.*[35]

The large utilities which neglected to invest significantly in renewable generation are now threatened by declining market shares and lower prices for conventional generation, particularly at hours of peak demand when PV is abundant (see

33 Although these are inspired by neoclassical economics, it is noteworthy that some neoclassical analysts participating in the debate, like Frondel et al., (2010), neglect external costs.
34 "That kind of competition" refers to price competition and competition within a rigid pattern of invariant conditions, methods of production and forms of industrial organisation.
35 Schumpeter, J. (1943, pp. 84-85), *Capitalism, Socialism and Democracy*, New York: Harper.

Chapter 2 and 11). In a perhaps overstated case of their pain, the Economist argues that deployment of renewables creates an "existential threat" to the large utilities, stating that

> *The country's biggest utility, E.ON, has seen its share price fall by three-quarters…and its income from conventional power generation…fall by more than a third since 2010. At the second-largest utility, RWE…net income has also fallen a third since 2010. As the company's chief financial officer laments, "conventional power generation, quite frankly, as a business unit, is fighting for its economic survival".*[36]

The current wave of investment in new coal generation plants in Germany – one of the biggest since post-war reconstruction– is likely to exacerbate that problem.[37] Indeed, Becker (2011) paints a dramatic picture of the prevailing relations between the two systems, fossil vs. renewables: two trains headed for each other at full speed on the same track, with a crash impending.[38] Hence, behind the ferocity of the discourse also lurk the vested interests of a threatened industry, forming a discourse coalition with those arguing for a passive state, aiming to protect a status quo which threatens future generations (see also Chapter 13).

Finally, the European Commission made several attempts in the past to ban "German-style" feed-in tariffs or at least to subject them to state aid control (which would probably come close to banning them). Up to now Germany was a strong opponent of such moves. Things are likely to be different with new Commission efforts under way in early 2014. In the name of affordability and industrial competitiveness, these proposals aim to slow down the shift to renewables via low targets for 2030 (27 per cent overall, just seven per cent more than for 2020) and strict limits to support for technologies as soon as they have a European market share of 1-3 per cent.[39] If adopted, this may well put an end to EEG-style energy system transformation and similar efforts elsewhere in the EU. It would be tragic if a weak and flawed cost discourse is allowed to contribute to such an ending.

36 Economist (2013), European Utilities: How to lose half a trillion euros. Europe's electricity providers face an existential threat, 12 October. http://www.economist.com/news/briefing/21587782-europes-electricity-providers-face-existential-threat-how-lose-half-trillion-euro, accessed 16 October 2013.In 2013, RWE made its first loss in sixty years, though only partly in connection with *Energiewende*.

37 (IEA 2013a)

38 Becker, P. (2011), *Aufstieg und Krise der deutschen Stromkonzerne*, Bochum, Ponte Press.

39 (European Commission (2013a), Draft guidelines for environmental and energy State aid, 2014-2020. http://ec.europa.eu/competition/consultations/2013_state_aid_environment/index_en.html

15

TOWARDS A STRATEGY FOR OFFSHORE WIND POWER IN SWEDEN

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INTRODUCTION

The first offshore wind power farm was built in 1991 (in Denmark) but the diffusion of wind turbines took place mainly onshore.[1] By 2013, European offshore turbines supplied 24 TWh but there are expectations of a supply of 140 TWh by 2020.[2] For 2030, UK and Germany expect the supply to increase to about 115 and 87 TWh respectively.[3] The longer term potential is much larger and in the European Commission's Vision 2050 scenario analysis, 800 TWh are supplied (see Chapter 3 on the global potential).[4] Hence, offshore wind power is seen as a strategic technology in EU's efforts to decarbonise electricity generation.

Multifaceted government policies are applied in mainly UK, Germany and Denmark to support development and deployment of offshore wind power, that is, interventions are not limited to forming a market but include other dimensions in the

1 This chapter draws on Jacobsson, S. and Karltorp, K. (2013). Mechanisms blocking the dynamics of the European offshore wind energy industry – challenges for policy intervention, *Energy Policy*, 63, 1182-1195; Jacobsson et al. (2013): Bidrag till en handlingsplan för havsbaserad vindkraft i Sverige – för säkrad eltillförsel, stabilt klimat och industriell utveckling, Report number 2013:11, Environmental Systems Analysis, Chalmers University of Technology. We are grateful to Västra Götalandsregionen for co-funding and providing an arena for discussing our work

2 Beurskens et al. (2011): Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States, ECN and European Environment Agency.

3 E.ON (2011): E.ON Offshore Wind Energy Fact book, E.ON Climate & Renewables, December, states that the goals are 33 and 25 GW respectively and we assume a capacity factor of 40%.

4 In European Commission (2011): Energy Roadmap 2050, {COM(2011) 885}, the average supply of offshore wind power in five decarbonisation scenarios is 234 GW, or 818TWh with 40% capacity factor.

industrialisation of the technology. Expectations of an extensive deployment are shared by many firms in the value chain, including component suppliers, turbine manufacturers, utilities, harbours, shipyards and logistics firms. A whole industrial system has begun to develop in northern Europe.

In this chapter, we argue that Sweden should shift from a passive to an active stance towards offshore wind power and initiate a process that eventually leads to a large-scale deployment. In the next section, we argue that offshore wind power is a desirable technology to develop in Sweden and we suggest a target for Sweden in 2030. This is followed by an analysis of mechanisms that may obstruct meeting that target and points to ways of overcoming these. In the final section, we discuss how a strategy for Sweden could be formed.

WHY BUILD OFFSHORE WIND TURBINES IN SWEDEN?

There is a significant potential for offshore wind power in Sweden, as there is in Finland and in the Baltic Sea Region at large.[5] An example may illustrate the scale involved. If (i) 3000 km^2 of a total of 30 000 km^2 of Swedish waters which the Baltic Sea Region Energy Co-operation (BASREC) judges to be attractive for offshore wind power is put aside for that purpose,[6] (ii) 5 MW is installed per km^2 and (iii) these have a capacity factor of 40% (3500 hours per year), the annual supply would be more than 50 TWh, or about one third of current Swedish supply of electricity. A number of firms have seen this potential and about 24 TWh could be produced in projects where firms currently either have or are applying for permissions to build offshore wind farms.

But, is an extensive deployment desirable in Sweden? In the debate, two arguments are frequently put forward against investment in new capacity to supply electricity from renewable energy sources. First, Sweden is currently a net exporter of electricity and is expected to remain so for some time.[7] Second, Sweden has already met its EU 2020 goal.

While correct technically, these arguments are weak in that they have a too short time horizon and focus on Sweden only. First, there is a considerable risk that a substantial production gap will emerge in Sweden, and in the larger Nordpool area, when the aging nuclear power plants (35 years on average) reach the end of their lifetimes. With, say, a 50 years' life-time, there may be a production gap of about 30 TWh for Sweden in 2032 and more beyond that date (Figure 15.1).[8] For Nordpool, the gap may exceed 100 TWh in 2035.

5 This includes the west coast of Sweden and the Danish isles.

6 BASREC (2012): Conditions for deployment of wind power in the Baltic Sea Region, Baltic Sea Region Energy Co-operation, April.

7 Naturvårdsverket (2012): Underlag till en färdplan för ett Sverige utan klimatutsläpp 2050, Bilagor till rapport 6537.

8 For nuclear power, we use the average production per reactor for the past ten years and add some supply since investments in new capacity have been made. For wind power and biopower, we use Swedish Energy Agency's (2013) long-term scenario from which we also have taken data on electricity demand. Their scenario ends in 2030 and the production of wind and biopower is assumed to remain at the level in 2030 (33 TWh). For hydro power, we use the average production 2003-2012 which was 65 TWh. See Jacobsson et al. (2013) for details.

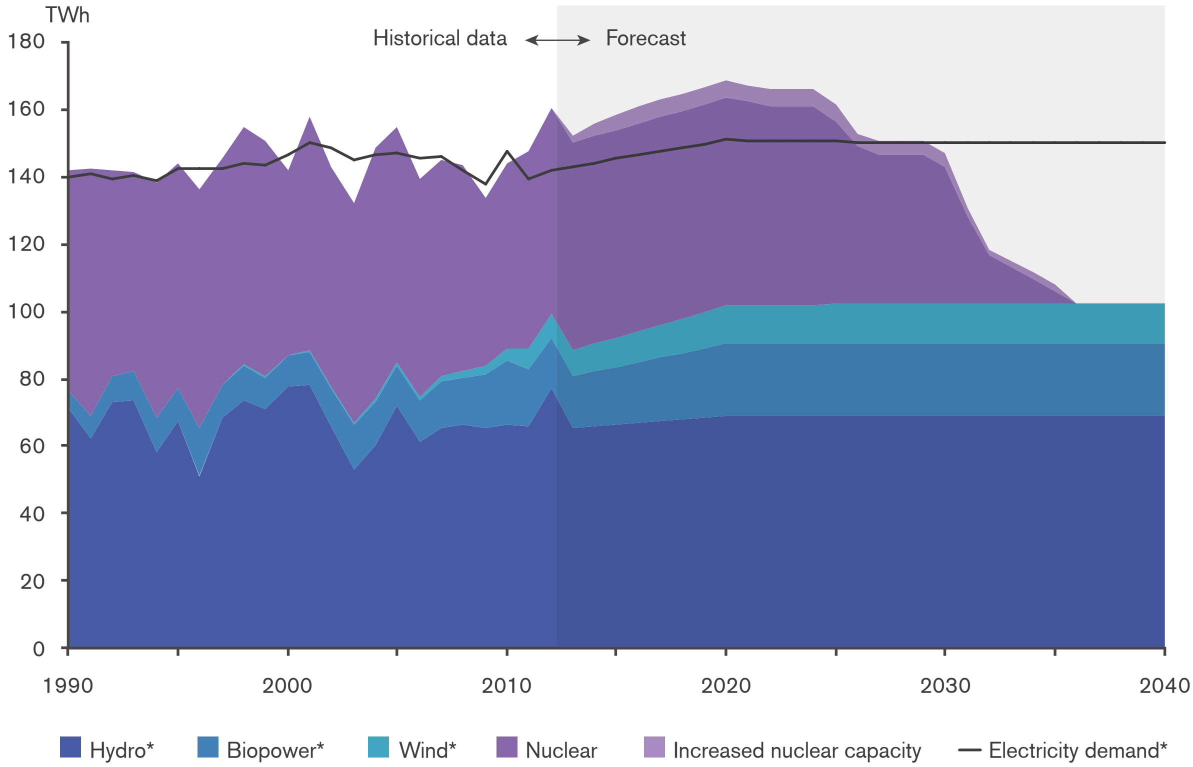

Figure 15.1 The emerging gap between electricity use and supply in Sweden. Source: Jacobsson et al. (2013).

Whereas the time-frame may be thought of as long, it is not long in the context of building new capacity. The environmental assessment of the Finnish nuclear plant in Olkiluoto started in 1998[9] and the reactor is not expected to be finished until 2016. Also offshore wind power farms have long lead-times. Several larger projects in Swedish waters expect to take about 15 years from the first idea to completion (Blekinge Offshore, Stora Midsjöbanken) and industry representatives emphasise the long lead-times of new projects – about 9-14 years.

Second, in the EU as a whole, the size of the expected production gap is immense – between 2020 and 2050 new investments may be required to supply close to 3000 TWh of renewable electricity (Figure 15.2).[10] It is, therefore, not helpful to frame the debate as if this were an irrelevant issue – Sweden is part of the EU and cannot be isolated from the implications of the goal of decarbonising the EU electricity supply in a few decades.

Initiating an extensive deployment now would, thus, contribute to ensuring that Sweden and Nordpool countries have access to the required volumes of electricity when the nuclear plants are taken off-line. The potential is also large enough to allow for a substantial contribution to meeting EU's goal through electricity export.

9 Energimyndigheten (2010): Kärnkraften nu och i framtiden, ER 2010:21.

10 In this scenario we have made the following assumptions: Electricity demand continues to increase at the same rate as between the years 2001 and 2010, i.e. 0.85% per year. This gives an electricity demand of nearly 5 000 TWh in 2050. All electricity generation from fossil fuels are phased out by 2050, a decrease of 1676 TWh. The life-span of existing nuclear plants is 50 years, which gives a production of 15.4 TWh in 2050, a decrease by 906 TWh. By 2020, the National Renewable Energy Action Plans estimate to add 578 TWh from renewable energy sources (Beurskens et al. 2011, p. 263). New nuclear plants are expected to produce 527 TWh, which is the average from the Energy Roadmap 2050 five decarbonisation scenarios. With these assumptions, there will be a need to invest in capacity to supply nearly 2900 TWh between 2020 and 2050. For more details, see Jacobsson et al.(2013). Through ambitious energy saving measures, the sum may be reduced but the challenge is still huge.

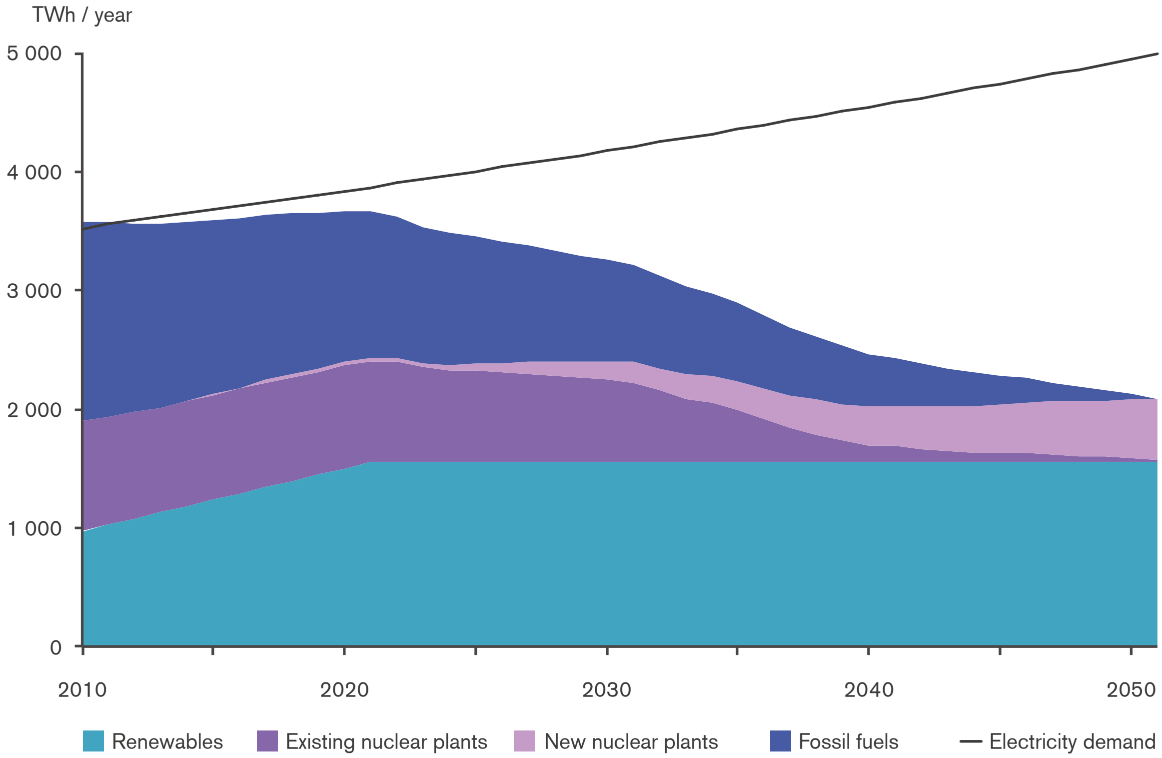

Figure 15.2 The emerging gap between electricity use and supply in EU, including Norway and Switzerland. Source: Jacobsson et al. (2013).

A deployment will be associated with new business opportunities. First, available evidence suggests that it is cheaper to generate offshore wind power in the Baltic Sea than in the North Sea. Indeed, it has been argued that with "inner-sea technology" costs may be up to 25-30% lower.[11] Sweden may, therefore, develop into a cost-efficient supplier of wind power. Second, a deployment would provide a home market for suppliers which may simplify for them to take shares of the emerging EU market – reaching a goal of 44 GW by 2020 is estimated to involve investment of about 135 billion EUR.[12] As Sweden has a strong engineering industry, this market may be a significant source of growth. Some firms are already in the industry, such as ABB in transmission, SKF and DIAB in components and GVA in marine technology. A home market would be expected to make it easier for firms in related industries to follow these and diversify into the offshore wind power supply chain. These firms may be found in e.g. steel, cement and shipbuilding industries, in shipping as well as in harbours. It may also benefit technology based start-ups, such as Hexicon, HM Power, Falkung Environmental Energy and SeaTwirl Energy Systems. Third, while these, and other firms, may supply products and services to North Sea applications, an early Swedish home market for "inner-sea technology" may provide an opportunity to develop new solutions that can be sold to other markets. This may even include turbines that are optimised for the wind conditions in the Baltic Sea

11 The conditions are less harsh in the Baltic Sea with less salty water and smaller waves, which influences the technology which is most appropriate, see e.g. Malmberg, H. (2012): Havsbaserad vindkraft i Östersjön. Inventering av frågeställningar och analys av förutsättningar för lönsamhet.

12 KPMG (2010): Offshore Wind in Europe - 2010 Market Report; Rabobank, (2011): Reaching EUR 10c/KWh… 10 ways to cut subsidies in offshore wind. Utrecht.

In sum, there are strong reasons for initiating an extensive deployment of offshore wind turbines. The Vision is to *ensure an adequate supply of electricity in Sweden and Nordpool by about 2030, contribute to EU's decarbonisation and induce industrial growth in Sweden.* It is harder though to set realistic goals with respect to deployment in Swedish waters. Varying, but long, lead-times make it problematic to assess the speed at which deployment may occur. However, if we assume that a supporting regulatory framework is in place in 2015 and if all farms with permissions are built, these could be in place between 2019 and 2023 and provide about 8 TWh/year. Farms for which permission is being sought could be built a few years later, providing about 12 TWh/year. With a supporting framework, we would expect yet more farms to be planned and built before 2030. Hence, by 2030, it is conceivable that 30 TWh could be supplied annually. Even if this figure is uncertain, it is noteworthy that it is close to the above estimated production gap in the early 2030s. Hence, a preliminary target may be set at 30 TWh/year (8.5 GW) by 2030.

This is an ambitious target for an industry which is still young and a considerable risk is that the supply capacity of the EU capital goods industry will not grow fast enough. In 2012, 1.2 GW was built in Europe, a figure which is expected to grow to 1.9 GW in 2014.[13] Reaching the Swedish goal of 8.5 GW by 2030 would, thus, mean that the capital goods industry would sell only to the Swedish market for more than four years. To reach the EU goals of 44 GW around 2020 and 234 GW by 2050, its capacity must increase significantly. While this illustrates the risks for significant bottlenecks, it also highlights the business opportunities involved. In the following sections, we identify a number of obstacles to an extensive deployment and discuss how they may be removed.

FORMING MARKETS

The Swedish Tradable Green Certificate system (TGC) is designed to induce investments in the lowest-cost technologies, which are currently onshore wind power and biomass CHP. For four reasons, it is an unsuitable regulatory framework to promote investments in offshore wind farms. First, costs for offshore may be 40-50% higher than for onshore.[14] This is particularly problematic today (2014) when the price of electricity is low at the same time as the certificate price is low. The combined revenue dropped from about 9 eurocents/kWh in 2010 to 5 in 2012.[15] Second, a strong fluctuation in the revenue streams creates uncertainties, in particular with the long lead-times involved, which is likely to increase the cost of capital.

Third, it is a quota-based system and when the quota is filled, the price of certificates drops. An investment in an offshore wind farm is so large that it may fill the quota and, therefore, lead to reduced income for *all* investors, including the firm that makes that investment. An extensive deployment of offshore wind power would therefore require a political guarantee that the quota is increased - a political risk. Fourth, if the quota increases at the rate required to induce an extensive

13 EWEA (2013): The European offshore wind industry – key trends and statistics 2012.
14 Malmberg, (2012); Elforsk (2011): El från nya och framtida anläggningar 2011, Sammanfattande rapport, Elforsk rapport 11:26;
15 Jacobsson et al. (2013)

deployment of offshore wind turbines, it would raise the price of the certificates[16] and, consequently, lead to large rents for investors in less costly technologies.[17]

For these reasons, we propose that another policy is used. Inspiration may be sought in three leading countries. The German feed-in law provides a fixed and technology-specific payment per kWh for a given number of years. The payment increases with distance from shore and a "sprinter bonus" is given to early investors. UK is shifting to a similar system and feed-in tariffs (strike prices) were recently published. Finally, Denmark applies an auctioning system where the winner receives a feed-in tariff.

Swedish Wind Energy [18] proposes an auctioning system which is adjusted to the Swedish context where a number of farms have permissions to build. While the proposal has merits, there are disadvantages too. Most importantly, auctioning generates an unattractive risk-to-revenue ratio. From the perspective of an investor in an offshore wind farm, there are significant uncertainties with respect to technology (including geo-technology), suppliers, construction, grid connection, market and politics. These risks are larger for early investors than for followers (as learning normally takes place) and investors compare these risks with expected revenues. A policy which, in an early phase in the development of the industry, can be expected to lead to the desired deployment must involve an attractive balance between revenue and these risks. An auctioning tool which prioritises lowest cost has a questionable credibility in that respect, even if the political risk is kept low and grid connection is guaranteed.

Long lead times in acquiring permissions (see below) add costs and risks and if investors need to do geotechnical studies (which are expensive) to be able to make a bid, costs will increase further. All in all, *an auctioning procedure is likely to be associated with high initial costs, low and uncertain revenues and many risks*. For an industry which is deemed to be strategic, these features are problematic.

We propose instead that a feed-in policy is developed to support the deployment of offshore wind turbines. A guaranteed and cost-covering payment for a number of years, with a certain risk compensation built in for early investors, creates a more attractive balance between risks and revenues. Cost reductions may be stimulated, as in Germany and UK, by a gradual reduction in feed-in tariffs for new projects. The main challenge is to set the tariffs, which requires that the government has the required technology-specific competence. Although the cost level is project specific, an initial tariff of around 85öre/kWh is perhaps of the right order of magnitude; less if investors do not pay for transmission lines to the national grid.[19]

As there is great uncertainty in the timing of the "retirement" of the current nuclear plants, an expansion in the capacity to supply electricity from offshore wind farms

16 This assumes that the quota cannot be met by deployment of onshore wind power.

17 Bergek, A. and Jacobsson, S. (2010): Are Tradable Green Certificates a cost-efficient policy driving technical change or a rent-generating machine? Lessons from Sweden 2003-2008, *Energy Policy*, 38, 1255-1271.

18 Svensk Vindenergi (2013): Särskild satsning på havsbaserad vindkraft, Svensk Vindenergi, April.

19 Elforsk, (2011); Malmberg, (2012).

needs to be combined with organising for a greater trade in electricity. This would involve an increase in the transmission capacity (see Chapter 9) and a regulatory framework which guarantees prices that cover costs. A framework could be agreed upon by Nordpool and be supplemented with bilateral agreements with other countries, such as Germany.[20]

PERMISSIONS AND MARITIME SPATIAL PLANNING

Different industries (e.g. fishing) compete over the marine space as does the military. Indeed, the military has objected to plans for a 2.5 GW farm (Blekinge Offshore) and constitutes a serious obstacle to deployment in Sweden. Environmental concerns put additional items on the agenda, including objections from coastal populations (see also Chapters 6 and 8). Applications for permission to build offshore farms are, therefore, often contested.

Within the Swedish territorial limit, it is also a complex process to apply for permissions, involving many actors, long lead-times, high cost and uncertainty for investors.[21] For instance, the project developer WPD had to make 11 different applications to get permission to build a farm (Storgrundet). The work was started in 2006 and in 2013 they reached the stage where they applied for permission to build the transmission cable.

The process of applying for permission has to be simplified and speeded up. It would help if parts of the sea are dedicated to offshore wind farms. So far, only a few European countries (Denmark, Germany and Britain) have done so but such areas are needed, as an element in a comprehensive maritime spatial planning, to reduce uncertainties for investors and the time and costs of acquiring permission.[22] The recently created Swedish Agency for Marine and Water Management has the responsibility to develop a comprehensive policy for the sea and it is vital that it develops a plan for offshore wind power (see Chapter 8 for a related discussion on other forms of ocean energy). It is, however, important that (i) the development of a plan does not delay investments in farms which already have permissions (ii) it is done in dialogue with project developers and (iii) the plan is flexible to accommodate for new technology and improved knowledge of the sea floor.

TRANSMISSION AND HARBOURS

Investors in offshore wind farms are obliged to pay for building the transmission cable and the connection to the land-based grid and, sometimes, to upgrade that grid. With an extensive deployment of offshore wind farms, the regulation risks leading to inefficiencies due to lack of coordination between investments in farms and the grid. Svenska Kraftnät[23] emphasises the importance of coordinating investments in the onshore grid and deployment of wind turbines. Similarly,

20 The supply of intermittent power grows quickly in Germany which may reduce the interest in buying intermittent power from Sweden (see Chapter 13, Figure 13.2). However, Germany has problems with its deployment of offshore wind farms, has a very large gap to fill (both coal and nuclear) and is tormented by a cost discussion (Chapter 14). Imports of relatively cheap Swedish offshore wind power may, therefore, be attractive.

21 Beyond the territorial limit, an investor only needs approval from the Government and the process is much easier.

22 Västra Götalandsregionen (2010): Förutsättningar för havsbaserad vindkraft, 09-10; BASREC, (2012).

23 Svenska Kraftnät (2012): Perspektivplan 2025 – en utvecklingsplan för det svenska stamnätet, Svenska Kraftnät.

an extensive deployment of off-shore wind farms would require a coordination of investments in these and in the offshore grid to ensure cost efficiency and supply security.

In Germany and UK, there is an understanding that it is not self-evident how an appropriate regulation looks like and both countries have made large changes in initial policies. These are made to make sure that investors, neither in the grid nor in wind farms, are landed with "stranded assets" and that investments in *different* offshore farms are coordinated with the investments in the grid – instead of building a separate transmission cables to each farm, synergies are created through a common infrastructure.[24] Cost efficiency may, therefore, require that farms are built in clusters which take us back to maritime spatial planning. Some of these clusters may come to cross borders which mean that there may be a need for coordination between countries. An example is E.ON's planned farm Södra Midsjöbanken and Polish farms on the other side of the border. As argued by several,[25] it may be advantageous to build transnational grids with a strengthened capacity for trading electricity across borders. This leads to the notion of building an international grid that connects several countries in the Baltic Sea region. Such a grid may also help handle uncertainties with respect to imbalances between supply and demand due to the uncertainties in the life-times of nuclear plants and the intermittent nature of wind power production (see Chapter 9).

Harbours constitute another vital infrastructure. A number of European harbours invest in facilities for supporting the deployment of offshore wind turbines. One of these is Bremerhaven and others are Cuxhaven and Belfast, the latter building a 100 000 m^2 facility.[26] This infrastructure is vital for deployment and service of the turbines but also as a base for manufacturers of components and turbines. Yet, costs for rebuilding harbours are high and in Britain, the government has allocated about 150 million EUR to support the transformation of harbours. For investments to be taken, it is vital that the regulatory framework for forming markets is credible, stable and long-term and that project developers agree to use a particular facility.

FINANCIAL AND HUMAN CAPITAL

A recurrent theme in the European debate is the gap between the volume of capital required to be invested in transforming the energy system and the volume that is currently invested.[27] Industrialists argue that lack of financial capital will constitute one of the largest obstacles to an extensive deployment in Sweden. To generate a capacity to supply, say, 30 TWh/year may cost in the order of 25 billion EUR (with current prices).[28] A necessary condition for this capital to be made available, at reasonable prices, is that there are long-term and stable regulatory frameworks which keep political uncertainties down.[29]

24 E.g. EoN (2011) and von la Chevallerie (2013): Clearer path ahead under new grid connection rules, Windpower Monthly, special report, April.

25 E.g. Deutsche Bank (2011): UK Offshore Wind: Opportunity, Cost and Financing.

26 Huss, M. (2013): Presentation by Martin Huss at Windforce Baltic Sea, Stockholm 20-21 February.

27 Jacobsson, R. and Jacobsson, S. (2012): The emerging funding gap for the European Energy Sector – will the financial sector deliver? *Environmental Innovations and Sustainable Transitions* 5, 49-59; Rubel et al. (2013): EU 2020 Offshore-Wind Targets. The € 110 Billion Financing Challenge, The Boston Consulting Group.

28 Elforsk (2011) cost estimates would lead to an investment cost of 311billion SEK. Based on indicated costs of current projects in Sweden we get 240 billion SEK. For the estimate in the text, we averaged these figures.

29 (Deutsche Bank, 2011; Rubel et al. 2013)

While such frameworks are necessary, they are probably not sufficient for a number of reasons that are further discussed in Chapter 16. First, utilities do not have the financial capacity to fund investments over their balance sheet, especially if they are engaged in several farms simultaneously. Second, financial actors associate offshore wind power with high risk and are therefore hesitant to invest, in particular before the farm has been built. Third, the financial crisis reduces access to capital from commercial banks. Finally, some banks have developed an extensive business which involves short-term speculative investments in financial products rather than long-term investments in industrial projects such as offshore wind farms.

Deutsche Bank [30]concludes that: *"Insufficient capacity in debt capital markets, perceived risk around policy support frameworks, risk around new technologies being rolled out ...have made low carbon infrastructure financing unachievable without scaled up Government intervention.*"

The German and UK governments responded by strengthening the role of public investment banks (KfW and Green Investment Bank), aiming to reduce the risks for private investors.[31] "Green bonds" is another option where a public bank, say SBAB in Sweden, issues green bonds for which the state acts as guarantor. Together with a guaranteed feed-in payment, this would not only take away the need for risk premium but also open up for e.g. pension funds to channel some of their capital into this industry. Creative solutions are, thus, required to ensure supply of sufficient capital, at a reasonable cost.

An extensive deployment also necessitates that specialised human capital is made available. This includes, e.g. operation and maintenance personnel, staff with competence in environmental impact assessment and PhDs in electrical engineering who are specialised in grid design and development (see Chapter 16 for a more detailed discussion). Blekinge Offshore, for example, estimates that 150 technicians for operation & maintenance will be needed. The scale of this challenge depends on the target for deployment and the level of ambition for industrial growth in the field. With a high level of ambition, bottlenecks will occur but these can be reduced by coordinating research and educational policy with energy and industrial policies.

RESEARCH AND INNOVATION

The cost of offshore wind power is expected to decline with increased deployment but a deployment further from shore, and in more difficult conditions, may offset the effects of learning. Moreover, learning requires dedicated efforts in the whole value chain, for example to create standardised solutions for combining foundations and turbines, net connections[32] and logistics.[33] Other examples are new turbine technology, new crane technology in harbours and ships to transport and install foundations and turbines.

30 Deutsche Bank (2011 p. 39)
31 KfW, for instance, invests 5 billion Euros in offshore wind farms.
32 Knight, S. (2013): Cabling standards hold key to cutting costs, Wind Power Monthly, Offshore special report, April.
33 Huss, M. (2013): Presentation by Martin Huss at Windforce Baltic Sea, Stockholm 20-21 February.

In order to stimulate technical change that reduces costs and enables industrial growth, the leading countries fund organisations for conducting applied R&D and contributing to innovation processes. Risø in Denmark is perhaps the most famous of these. In Germany, a Fraunhofer institute dedicated to offshore wind power was created in 2005 and in Britain, the Offshore Renewable Energy Catapult was recently founded, inspired by the Fraunhofer Institute.

The applied R&D focusses on solving problems associated with the severe conditions in the North Sea. For Sweden, and other countries around the Baltic Sea, "North Sea" technology needs to be supplemented with technology which is adjusted to the specific conditions in the Baltic Sea, i.e. "inner sea technology". As mentioned earlier, the difference may constitute an opportunity for firms developing along a somewhat different technological trajectory. In part, attractive market conditions will induce such efforts but these may be supplemented with an applied RD&D (research, development and demonstration) program (co)funded by the state and involving universities of technology. While the details of such a programme cannot be specified, some examples of knowledge fields may be given:[34] foundations, including those that can manage ice and technology to install foundations; turbines which are dimensioned to wind conditions in the Baltic Sea; logistics solutions (including specialised ships) and transmission solutions. A further area would be floating turbines – a technology which is independent of sea floor conditions and which builds on marine technology, a strength in Sweden.

CONCLUDING DISCUSSION

In this section, we summarise our findings and identify further issues in forming a strategy for Sweden. Although an extensive deployment of offshore wind turbines is contested, we have argued that it is desirable in order to (i) ensure an adequate supply of electricity in Sweden and Nordpool by about 2030 (ii) contribute to EU's decarbonisation and (iii) induce industrial growth. We have also argued for a target of about 30 TWh in 2030.

Market	Design a feed-in law that provides an attractive balance between risks, costs and revenues for investors
Permission	Organise the application process for permission to reduce lead-times and costs, inter alia though maritime spatial planning
Transmission	Find a regulatory framework for extending the onshore and offshore transmission grid that guarantees connections and simplifies coordination of investments within and across borders
Harbours	Create long-term targets as well as stable and attractive conditions necessary for harbours to undertake investments
Financial capital	Secure access to the capital required for an extensive deployment and at reasonable costs
Human capital	Secure access to specialised human capital
R&D and innovation	Form a RD&D program with particular emphasis on technical solutions appropriate for the Baltic Sea

Figure 15.3 Policy challenges for offshore wind power in Sweden.

34 Dalén, G. (2013): Presentation by Göran Dalén at Windforce Baltic Sea, Stockholm, February 20-21.

As in other countries, the strategy to reach this goal needs to be multifaceted. With respect to market formation policy, we proposed a feed-in law in order to find an attractive balance between risks, costs and revenues for investors. An effective strategy would also need to incorporate policies that help overcoming obstacles in sex other areas, see Figure 15.3

It is urgent to develop and implement the strategy due to the long lead-times in many fields. We have referred to those in planning and building the farms but they are also present in planning and building transmission grids and in rebuilding harbours. Moreover, there are long lead-times in changing regulatory frameworks, developing new educational programmes and setting up, conducting and benefitting from an RD&D programme.

The range of challenges indicates that several government departments and agencies need to be involved in formulating and implementing a strategy. We have mentioned the Swedish Agency for Marine and Water Management and Svenska Kraftnät (the Swedish National Grid) but there are more, including the Ministry Education and Research and Ministry of Enterprise, Energy and Communications as well as the Swedish Energy Agency. Their respective policies need to be coordinated.

Coordination with other countries in the Baltic Sea region may also be desirable, e.g. in terms of grid development. This adds complexity but there are also advantages. Collaborating with Finland, for instance, could give several advantages. First, as the physical conditions resemble those in Sweden, coordinating RD&D programmes may reduce costs and strengthen industrial growth in both countries. Second, with a common market formation programme, the region would be more attractive for firms in the whole value chain. It may, for example, require 500-600 turbines to be built over a two-year period in order for firms to undertake investment in a specially designed ship to transport and install the turbines. Collaborating with Finland would, therefore, be a way to enhance industrialisation in the region as a whole. The form for collaboration may be inspired by the German-French coordination of ”Energiewende” with a joint office for renewable energy.[35] Third, in order to reduce the negative effect of intermittent supply, a plan for locating turbines across the Baltic Sea may be useful.

Finally, as for further issues to explore in forming a strategy, we need to ascertain the cost advantages of “inner-sea technology” and establish how to manage the intermittent supply of wind power (Chapter 9 and 11). Again, we need to acknowledge the time horizon. If our target is met, there is close to two decades available to solve the issue of intermittency. We should also acknowledge the potential growth that may come out of finding solutions, e.g. in the form of electricity storage (Chapter 5 and 12) and demand-side management technologies (Chapter 10).

35 Altmeier, P. and Batho, D. (2013). Gemeinsame Erklärung über die Zusammenarbeit im Bereich erneuerbarer Energien und die Schaffung eines Deutsch-französischen Büros für Erneuerbare Energien im Rahmen der Energiewende.

16

THE NEED FOR FINANCIAL AND HUMAN RESOURCES – THE CASE OF OFFSHORE WIND POWER

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INTRODUCTION

Increasing the share of renewables in the European energy system constitutes a large technical challenge, for example in terms of developing and deploying new electricity generating technologies, grid infrastructure and energy storage (Chapters 4-5, 9-12 and 15). A large-scale transformation of the energy system also requires a successful management of non-technical challenges in many areas. We will focus on two such challenges which constitute generic problems in large-scale transformations.

First, the financial sector must address the increasing need for financial resources to enable substantial investments in renewable energy technologies. Until 2020, the European Commission argues that energy-related investments of about 1 EUR trillion (corresponding to about 6 per cent of EU's total investments during the time period) is needed.[1] Although the flow of investments into renewable energy in Europe has increased, it is estimated that this flow will be too low to reach the

1 European Commission (2010). Energy 2020 - A strategy for competitive, sustainable and secure energy, COM(2010) 639.

targets set up for 2020 and there will be an annual lack of funding in the range of 25-50 EUR billion,[2] corresponding to about 1-2% of total national savings in the EU member states. Second, universities must provide specialised competences, in time and in adequate numbers, to support the development and large-scale deployment of a whole range of new technologies. This chapter discusses challenges in securing the necessary financial and human resources for development and large-scale deployment of one of many technologies: offshore wind power.[3]

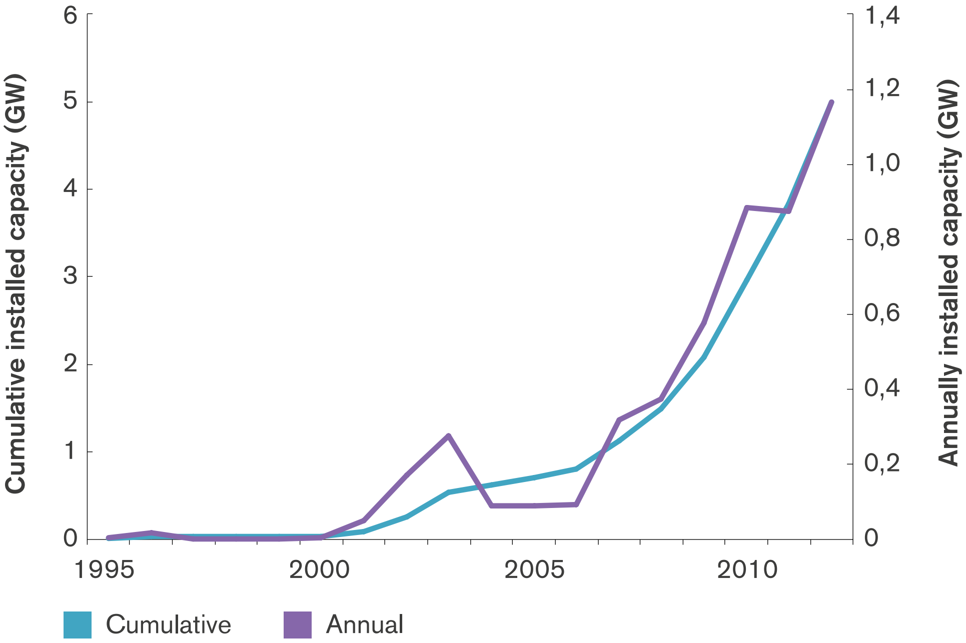

Figure 16.1 Cumulative and annual installations of offshore wind power in Europe. Source: (EWEA 2013)

Offshore wind power has the potential to contribute with significant amounts of carbon-neutral electricity in Europe. The first farm was commissioned in 1991 and the cumulative installed capacity had grown to 4.9 GW in Europe by 2012 (Figure 16.1). The National Renewable Energy Action Plans of the EU member states indicate that by 2020, 44 GW (generating some 140 TWh/year) of offshore wind power could be installed.[4] This could correspond to more than 10% of the renewable electricity in EU 2020. Moreover, the long-term potential is much larger; an elaboration of the vision presented by the European Commission (2011) indicates that more than 800 TWh could be generated from offshore wind power in 2050.[5]

2 De Jager et. al. (2011). Financing Renewable Energy in the European Energy Market. Ecofys, Fraunhofer ISI, TU Vienna EEG and Ernst & Young. Jacobsson, R. and Jacobsson S. (2012). The emerging funding gap for the European Energy Sector-Will the financial sector deliver? Environmental Innovation and Societal Transitions 5:49-59.

3 Analyses of all challenges for offshore wind power in Europe are provided in Jacobsson, S. and Karltorp, K. (2013). Mechanisms blocking the dynamics of the European offshore wind energy innovation system - Challenges for policy intervention. Energy Policy 63:1182-1195; and Wieczorek, A. J. et al. (2013). A review of the European offshore wind innovation system. Renewable and Sustainable Energy Reviews 26:294-306. A specific analysis of the case of Sweden is found in Chapter 15.

4 Beurskens, L. W. M. et al. (2011). Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States. ECN and European Environment Agency.

5 The average supply of offshore wind power in five decarbonisation scenarios is 818 TWh (234 GW), assuming a capacity factor of 40%. European Commission (2011). Impact Assessment to the Energy Roadmap 2050, SEC(2011) 1565.

FINANCIAL RESOURCES

The investment necessary to reach 44 GW by 2020 is estimated at 130 -150 EUR billion.[6] So far, utilities have funded the main part of the investments from their own balance sheets and through debt in the form of project finance from commercial banks.[7] The European Investment Bank (EIB) and export funding agencies (e.g. Danish Eksport Kredit Fonden) have played a vital role by providing capital and taking on a larger part of the risks in order to stimulate commercial banks to provide project finance. An additional funding source is the German Bank for Reconstruction (KfW) with an offshore wind energy program of 5 EUR billion for 10 projects. In line with this, the recently created Green Investment Bank in the UK has offshore wind as one priority.[8] However, the capital may be insufficient as only 3 EUR billion are allocated to a broad range of technologies.[9]

Only a few examples of venture capitalists and private equity firm's involvement have, so far, been seen in the construction of offshore wind farms and in other parts of the industry emerging around these farms. One example is Blackstone's leading investment in the German offshore wind farm Meerwind. A few institutional investors, e.g. pension funds, are also involved in funding offshore wind farms. For example PensionDanmark is together with another pension fund, PKA, majority shareholder in Anholt, the largest offshore wind farm under construction in Denmark.

CHALLENGES IN MOBILISING FINANCIAL RESOURCES

There are several challenges in mobilising the financial resources needed to scale up the deployment of offshore wind farms.[10] To grasp these challenges, it is necessary to understand what makes actors within the financial sector take the decision to invest in an emerging technology or not. The risk-return ratio is key to the investment decision. The following categories of risk can be assessed: *technological risk* that a technology will not operate as expected; *construction risk* that something goes wrong during the construction; *operations and maintenance risk* relates to the uncertainty about operations and maintenance, particularly what it will cost; *market risk* concerns the possibility of predicting the future market both in terms of price and volume; *supply risk* concerns if resources become scarce and *political risk* is the uncertainty about the future regulatory framework. The return depends on cost and income. For the investment decision, both the total cost of the investment and the cost per unit of output are important. To stimulate investments in renewable energy technologies, policies are used to adjust the risk-return ratio. However, the introduction of a policy can also lead to a political risk.[11]

6 KPMG (2010). Offshore Wind in Europe - 2010 Market Report. De Jager et. al. (2011). Financing Renewable Energy in the European Energy Market. Ecofys, Fraunhofer ISI, TU Vienna EEG and Ernst & Young.

7 Fulton et al. (2011). UK Offshore Wind: Opportunity, Cost and Financing. DB Climate Change Advisors. Rabobank and BNEF (2011). Offshore Wind: Foundations for Growth. Rubel, H., K. et al. (2013). EU 2020 Offshore Wind Targets - The €110 Billion Financing Challenge. The Boston Consulting Group.

8 KfW Bankengruppe (2011). Information Sheet on KfW Offshore Wind Energy Programme. Department of Business Innovation and Skills (2011). Next steps for the Green Investment Bank. Press notice.

9 Rabobank and BNEF (2011). Offshore Wind: Foundations for Growth

10 See Karltorp (2014). Challenges in mobilising financial resources to renewable energy, submitted for publication, for further details and references.

11 Wüstenhagen, R. and Menichetti, E. (2012). Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research. Energy Policy 40:1-10. Mitchell, C. et al. (2006). Effectiveness through risk reduction: a comparison of the renewable obligation in England and Wales and the feed-in system in Germany. Energy Policy 34:297-305.

The first challenge is that the hitherto main source of finance (balance sheet funding at utilities) will not be sufficient as utilities have an increasing number of farms planned in parallel with other investments to fund. External investors must, therefore, provide the needed capital.

Second, the financial crisis has caused a reduction of the liquidity in the market for project finance, i.e. funding where only the project itself is used as safety for the loan. Thus, it now takes more banks to do project finance (as each bank can provide a smaller part of the total investment), which increases complexity and cost. In addition, the introduction of a new piece of legislation, Basel III, with a stricter regulation of the capital-asset ratio, may further reduce the availability of debt. As a result, access to capital is reduced and the time horizon for this type of finance may be decreased from up to 15 to 7-8 years, implying that borrowers might have to seek finance several times during a project's lifetime. Thus, even though project finance has been a way to fund offshore wind, it is not likely it can match the financial resources needed for a large-scale deployment of offshore wind.

Third, many external investors associate offshore wind with large risks (and low returns) and therefore hesitate to invest. Even though there are numerous offshore wind plants in operation, there are still technological risks and as wind farms move further from shore and into deeper waters there are new technical challenges with e.g. grid connection and construction of foundations.[12] The complexity of constructing an offshore wind farm and the large number of contractors usually involved also cause construction risk. O&M risk is a result of the fact that the industry is young and knowledge of operation, maintenance and deconstruction at the end of the turbines lifetime is still weak. Market risk and political risk vary from one country to another.

In addition, the construction of an offshore wind farm is very costly, both in terms of the total cost and cost per unit of output. Total cost of an offshore wind farm typically amount to 1-1.5 EUR billion (in 2012, the average size of a farm was 130 MW).[13] The cost of the electricity generated is in the range 0.06 – 0.18 EUR/kWh, which can be compared to the cost of onshore wind power of 0.05- 0.09 EUR/kWh.[14] The returns, and the possibility to make profit from a project is, therefore, very much dependent on policy intervention. Examples of strong market supporting policies are found in the UK and Germany, while the opposite prevails in the Netherlands and Sweden.[15] The third challenge is that without strong policy support, offshore wind power is an investment with not only high risk but also with low returns, which implies that significant political and market risks exist for offshore investments, in particular as these have a life-time of 20-25 years.

Fourth, venture capitalists are the type of investors that take high risk. However, the size of investment needed and the long life-time of an offshore wind project

12 De Decker, J. et. al. (2011). OffshoreGrid: Offshore Electricity Infrastructure in Europe. Kaldellis, J. K. and Kapsali, M. (2013). Shifting towards offshore wind energy-Recent activity and future development. Energy Policy 53:136-148.
13 KPMG (2010). Offshore Wind in Europe - 2010 Market Report. EWEA (2013). The European offshore wind industry: key trends and statistics 2012.
14 Rabobank (2011). Reaching EUR 10c/KWh… 10 ways to cut subsidies in offshore wind. Kaldellis, J. K. and Kapsali, M. (2013). Shifting towards offshore wind energy-Recent activity and future development. Energy Policy 53:136-148.
15 Söderholm, P. and Pettersson, M. (2011). Offshore wind power policy and planning in Sweden. Energy Policy 39:518-525.

do not fit well with the investment model of venture capitalists. Typically, these investors prefer investments with high risk and high return and a relatively short time horizon.

Fifth, institutional investors manage assets in the magnitude required for offshore wind farms and could provide the financial resources needed. However, these investors normally do not take high risk and are not used to invest directly in projects with emerging technologies. An exception is the Danish utility Dong which has managed to get institutional investors involved by employing an innovative business model, where Dong sells parts of offshore wind farms, but still takes the construction risk. The challenge is, therefore, to reduce risk and stimulate investments from institutional investors that are not used to invest directly in assets such as offshore wind.

Finally, in the last decades the financial sector has engaged in a great deal of speculation focussing on short-term, high risk investments with great profit potentials. This might be interpreted as a general lack of interest in typical utility projects with long-term project funding, high risk and low rates of return.[16]

HOW TO MOBILISE FINANCIAL RESOURCES

Policy makers can improve the risk-return ratios by introducing support systems such as the feed-in-tariffs operating in Germany which reduces market risks and improves returns. It is important that such measures are stable and developed in a transparent process in order to limit the political risk. At the same time, an important way forward for the industry is to reduce cost in order to increase the return. This will also make offshore wind power projects less dependent on support systems.[17]

As the offshore wind power industry becomes more mature (and associated with less risk) new actors, such as institutional investors, might be willing to invest. In the meantime, one way forward is to strengthen the lending and risk-absorption capacity of public investment banks. The European Investment Bank and KfW in Germany provide successful examples of this.

Another way is to set up bonds with the specific purpose to finance renewable energy technology.[18] For example, a bank could set up a “Climate Bond” on the bond market and associated capital would only be allowed for financing of climate-friendly projects. A state or municipality could reduce risks by acting as a guarantor and committing to buy electricity generated from the projects. Such bonds may attract not only institutional investors that wish to invest in climate-friendly project, but cannot invest in these types of projects directly, but also other sources of capital, such as private individuals.

16 Jacobsson, R. and Jacobsson S. (2012). The emerging funding gap for the European Energy Sector-Will the financial sector deliver? Environmental Innovation and Societal Transitions 5:49-59.

17 The recent development in the solar PV industry illustrates this effect. A history of subsidised markets has enabled cost reductions through learning and economies of scale. In 2014, this cost reduction has made PV expansion partially independent of government support on several markets.

18 Mathews, J. A. et al. (2010). Mobilizing private finance to drive an energy industrial revolution. Energy Policy 38:3263-3265.

As the risk linked to an emerging technology might be perceived as higher than it actually is, technology developers may benefit from educating investors. This would enable potential investors to more accurately evaluate the specific risks linked to an investment opportunity in e.g. offshore wind. Another solution is that the investors themselves acquire the needed competence, e.g. through recruiting senior staff from the offshore wind industry.

Technology developers can also introduce business models with novel ways of sharing risks in order to attract investors that otherwise would hesitate due to too high risks. For example, if the technology developers absorb some of the technology and construction risks it may be possible to involve institutional investors on a larger scale. As mentioned above, an example of this is Dong's collaboration with Danish pension funds.

A summary of the challenges of mobilising financial resources to offshore wind and the suggestions of how to overcome these are presented in Figure 16.2.

HUMAN RESOURCES

An adequate supply of human resources is another critical factor for the development and deployment of offshore wind farms.[19] By 2030, European Wind Energy Association estimates that almost 300 000 will be employed in the offshore wind energy industry, up from 35 000 today. There is already a shortage of staff. For example, manufacturers of turbines report shortages of engineers, operation and maintenance staff and on-site managers.[20] In this section, the need for human resources is illustrated by the need for engineering competences. This is a key area of competence for the development of the offshore wind industry but, of course, not the only type of competences needed.

It is vital to supply the needed human resources both in terms of numbers and types of competences. An analysis of the number of engineers needed suggests that about 10 000 additional staff may be required in Europe until 2020.[21] The main part of these engineers is needed by turbine manufactures, but also utilities and other parts of the supply chain require many engineers.

Scrutinising the types of competences needed, the main bottleneck is a shortage of electrical engineers. These are required to strengthen the onshore grid, build an offshore grid and facilitate a large-scale integration of wind power into the power system. They are also needed by turbine manufacturer and some component suppliers. Specialised engineering competences are also needed in mechanical engineering, engineering physics, software engineering and civil engineering.

19 The case of the emergence and growth of an electronics industry demonstrates the significance of the challenge in that there was a poor responsiveness of the Swedish higher educational sector to growing technological opportunities, at least compared to the US. Indeed, for some years, the number of graduated engineers per capita in the US was over three times that in Sweden. Of course, Swedish industry suffered from lack of competences for many years. Jacobsson, S., et al. (2001). Alternative specifications of the institutional constraint to economic growth - or why is there a shortage of computer and electronic engineers and scientists in Sweden? Technology Analysis and Strategic Management, 13(2):179-193.
20 EWEA (2011). Pure Power - Wind energy targets for 2020 and 2030. EWEA (2011). Wind in our sails - The coming of Europe's offshore wind energy industry.
21 See Jacobsson, S. and Karltorp, K. (2012), Formation of competences to realize the potential of offshore wind power in the European Union, Energy Policy 44:374-384, for further details and references related to this section.

There is also a need for engineers who integrate hitherto distinct knowledge fields, e.g. electrical and mechanical engineering for the design of turbines. Hence, there is a demand for engineers who understand wind turbines as a whole, including e.g. aerodynamics, lightweight constructions and gearboxes and have the ability to optimize designs, bearing in mind the various loads. Engineers with this integrative competence are currently few, work as product development managers and have developed their competence on the job.

Other examples are engineers with competence in non-engineering fields, such as meteorology and project management. Indeed, project managers constitute a major bottleneck. An engineering background may be suitable for project managers, but they also require knowledge of logistics, finance, risk management and communication as well as an understanding of certification bodies, approval processes and insurance. In addition, health, safety and environmental impact are important knowledge fields for staff working offshore.

There is also a need for more PhDs as some tasks requires deep specialist competence. A case in point is the design and construction of offshore grids where more specialists in HVDC are required. The company Vattenfall alone may require 20-25 PhDs, staff that is not available today.

THE EDUCATION SYSTEM TODAY

Measures have been taken to address some of the current and anticipated shortages. Denmark, with a leading position in the wind turbine industry, has MSc and PhD programs dedicated to wind energy at both Aalborg University and Danish Technical University (DTU). Wind energy education for professionals is offered by Danish University Wind Energy Training and by DTU.[22] Germany has created MSc programs in Bremerhaven, Flensburg, Hannover and Oldenburg. Training for professionals is offered by ForWind and Education Centre for Renewable Energies. PhD training is conducted at several universities and institutes, such as IWES. Another centre for training and education is TU Delft in the Netherlands. As from 2012, it offers a European Wind Energy MSc in collaboration with DTU, the Carl von Ossietzky University of Oldenburg and the Norwegian University of Science and Technology (TU Delft 2012).[23]

In the UK, the measures are more recent and there are shortages of engineers to offshore wind power. Funding has been made available for an Industrial Doctorate Centre to help develop the skills for accelerating offshore renewable technologies – all in all 50 PhDs are to be trained. While several universities offer MSc programs in renewable energy, only the Wind Energy Engineering MSc program at the University of Central Lancashire is specialised in wind power.[24] Training for professionals is, however, given by Northumberland College and a “renewable energy centre at the Grimsby Institute is to become the first of its kind in the world to train the next generation of offshore engineers”. Finally, RenewableUK designed and set up an apprenticeship program supported by industry and handed it over to National Skills Academy.

22 Danish University Wind Energy Training (2011).
23 TU Delft (2012). European Wind Energy Masters.
24 Cordes, J. (2011). Where to go for wind power qualifications. Windpower monthly.

HOW TO MOBILISE HUMAN RESOURCES

To overcome the current shortage of competences, industry recruits staff from a range of related industries, i.e. industries with overlapping knowledge bases. For instance, aerodynamic engineers may be recruited from the automobile industry to work with wind farm design and material science specialists (for blade design and construction) from the shipbuilding industry. Yet, as industry expands, the particular needs of the offshore wind energy industry should be reflected in the programs and curricula at the universities. As described above, there are some programs that address this need, e.g. in Copenhagen, Delft, Oldenburg and Aalborg. These pioneering programs have to be supplemented with many others if industry is not to suffer unduly from a shortage of competences over the next decades.

First, more programs for developing deep competences, such as in electrical and mechanical engineering, are required. Second, there is a need for broad programs, integrating different engineering competences. A particularly challenging task is to integrate electrical and mechanical engineering. Neither in Denmark, nor in Germany do such programs exist at the MSc level at universities. There is also a need for programs that combine engineering competences with competences from other disciplines. In particular, programs in project management are needed.

With a few exceptions (e.g. DTU and Risö in Copenhagen), universities may not have a research base which is large enough to offer many types of specialisation. Offering a broad MSc program as well as many options for gaining deeper competence in selective fields may, therefore, be limited to the larger universities with a long engagement in wind power research. This raises the possibility of organising a European portfolio of specialised courses that are organisationally integrated and made easily available to students from universities taking part in the program. As mentioned above, a program of this type has started at TU Delft together with three other universities, but this program could be complemented by more initiatives. In addition to setting up programs, it is important to work with increasing the interest of young people in studying engineering and for securing an interest in offshore wind programmes among these.

Expanding the number and types of programs requires the teaching staff to be enlarged. With a time lag of some years, this can be achieved by increasing the number of PhDs, which necessitates an associated expansion in government R&D funding. Enlarged PhD programs are also needed to develop the human capital required to manage the complexity of many of the tasks facing the industry, e.g. in the design of offshore grids. However, in order for universities to adjust programs and curricula according to the needs of industry, it is essential that industry expresses its need for competences. This can be facilitated by joint projects and the formation of strong networks between industry and academia.

CONCLUDING REMARKS

To mitigate climate change, renewable energy technologies must be deployed on a large scale. Achieving this requires technical development as well as non-technical changes, including adjustments within the financial and educational sectors. This chapter has discussed a range of challenges with securing financial and human resources needed for development and deployment of offshore wind power in Europe. A summary of the challenges and some suggestions of how to overcome these are presented in Figure 16.2.

Resource challenges to reach 40 GW offshore wind power in EU 2020

Financial resources – Challenges

- Need for financial resources, as utilities cannot finance to same extent as before and project finance market is limited
- High risk and high cost/low return
- Venture capitalists invest in high risk, but cannot invest in the large size or for the long time needed
- Institutional investors could be an option, but not used to invest directly in emerging technology
- Speculation on the financial market

Suggestions for solutions:

- Increase risk-absorption capacity of public investment banks
- Technology development to reduce cost
- Policy support
- “Renewable energy bonds”
- New business models
- Increase knowledge of renewable energy at investors

Human resources – Challenges

- Need for engineers with specialist competence, particularly in electrical engineering
- Need for integrated competences, both different engineering fields and non-engineering competences (e.g. project management)
- PhDs competence needed to solve complex tasks
- Time lag for development of new competences
- Industry need to express their need of human resources

Suggestions for solutions:

- Programs for developing deep competences
- Programs for developing integrated competences
- Increased coordination between European universities
- Increased number of PhDs
- Industry – academy collaboration

Figure 16.2 Challenges related to the mobilisation of financial and human resources required for reaching the 2020 targets for offshore wind in EU and some suggestions how these challenges could be overcome.

The challenges to mobilising financial resources is that sizable investments are needed at the same time as offshore wind is still linked to high risk and low returns. Policy measures to improve the risk-return ratio and to strengthen the capacity of public investment banks are two ways forward. Institutional investors have access to huge amounts of capital but these investors are not used to invest directly in emerging technology projects. Renewable energy bond may open up that source of capital as may increasing institutional investors’ knowledge of offshore wind power and providing new business models where risk is shared between utilities and external investors.

To address the large need for engineering resources, both specialist and integrated programs are needed. PhD competence is needed to solve complex tasks and to supply teachers to these programs. Increased coordination between European universities can be a mean to increase the possibility for engineers to specialise within wind power. Collaboration between industry and academy is important to correctly address the need for competences and to limit the time lag in supplying these competences.

In this chapter the case of offshore wind power has been used to illustrate the challenges of mobilising financial and human resources. We have demonstrated that knowledge of the industry in question is required to understand the specifics of the challenges, e.g. the types of competences that universities need to develop. As many other renewable energy technologies have similar characteristics as offshore wind, e.g. high risk, a long project life-time and the need for new competences that combine knowledge fields in novel ways, they are likely to face similar challenges. Moreover, development of several technologies in parallel will multiply the demands on the financial and educational sectors. We would, therefore, argue that this kind of analysis need to be multiplied in order for us to be able to design appropriate policies that support a large scale transformation of the energy sector.

A SERIES OF EVOLVING E-BOOKS

The energy and climate challenge is enormous and the world is running full speed ahead into a very uncertain future. The role of technology is ambiguous: definitely part of the problem, but as surely, a necessary element of any transition to a more sustainable development. Hence, there is an urgent need to learn more about how to govern technical change.

"Systems perspectives on..." was initiated within Chalmers Energy Initiative. We set out to make a cross-disciplinary effort to evaluate technologies, in terms of benefits and drawbacks, and assess the technical, economic and political requirements for successful deployment and diffusion. We realised that this aim required something that was not only a product but also a process. The result is a series of evolving e-books. The ambition is to provide a platform for learning about systems issues related to critical technology areas. The series now comprises three books.

> **Systems Perspectives on Renewable Power** investigates the potential to harness renewable energy flows to replace non-renewables and satisfy the varying demands for electrical power.

> **Systems Perspectives on Electromobility** elaborates on the consequences and requirements of a transition to a transport system powered by electricity.

> **Systems Perspectives on Biorefineries** explores the potential and desirability of biomass as carbon and energy feedstock in the numerous applications currently relying on fossil fuels.

At this point we can conclude that, while there are still plenty of hurdles to pass and pitfalls to avoid, the future is not without hope.